Tranquillity by design

Architectural and landscape interventions to improve the soundscape quality in urban areas exposed to aircraft noise

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This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. It does not exceed the prescribed word limit for the relevant Degree Committee

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Abstract

Title: *Tranquillity by design - Architectural and landscape interventions to improve the soundscape quality in urban areas exposed to aircraft noise*

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The noise emissions from aircraft negatively impact the quality of life for those in areas around airports. Excess noise levels can cause stress-related complaints, leading to adverse health effects. Although newer aircraft are significantly quieter than older models, aircraft noise pollution remains a problem. Literature suggests that the level of aircraft noise annoyance people experience is equally dependent on the level of disturbance induced by the sound and individuals' perceived level of their own ability to cope with and control it. Traditionally, noise prediction models are used to determine the noise load around airports. If levels are deemed too high, building restrictions are put in place, and house owners are either bailed out or receive funding for acoustic insulation. However, literature on road traffic noise shows that the design of the environment that surrounds individuals has a great impact on their perception of noise annoyance. For instance, the design of buildings, streets and cities influence the propagation of sound around buildings. This can reduce or amplify the sound levels locally. Furthermore, the presence of natural features, such as trees and moving water, can evoke a more positive auditory sensation in areas exposed to traffic noise. Without changing the sound exposure levels, the sight and proximity of vegetation improves the individuals' assessment of the soundscape quality and reduces the level of noise annoyance. Like landscapes, the perception of the acoustic environment, or soundscape, is the result of design choices.

Nevertheless, the question remains as to whether the design of the built environment can yield a similar effect for aircraft noise. The doctoral research focused on this question, from both an acoustic and soundscape-perception perspective, and comprised four separate studies. The first study presents the results of a systematic in-situ measurement study, in which the sound attenuating effects of buildings exposed to aircraft noise were assessed. In the second chapter, the results from the first study were used to develop and test a method to predict the propagation of aircraft noise around buildings in a numerical acoustic model. The third study used the numerical model to compare the noise attenuation effects of building design parameters, namely height, form and cladding. The fourth chapter explored the perception of aircraft noise in urban areas with or without moving water and vegetation, using virtual-reality. Together, the four studies provide tools that can be used by architects and urban designers to improve the soundscape quality in areas affected by aircraft noise. Depending on the location and local acoustic situation, different alternatives are possible, which are supported by the results presented in this thesis.

Preface

As a frequent traveller between Amsterdam and Cambridge, each time I travel to an airport I am amazed by the coming and going of the airplanes. Inevitably, the closer you get to the airport, the harder it is to escape from the noise. By arrival at the airport, the traveller is met by a cacophony of sounds from horns, car engines, trains, humans and airplanes. Although the sound levels are acceptable inside the airport's terminals and gates, the levels are far less enjoyable outside the airport's premises, especially when standing close to the runway. The rapid growth of civil aviation, , partly driven by the rise of low-cost carriers, has dramatically increased the number of flight movements above (European) cities. Unfortunately, flying comes at a price and erodes the quality of living in areas close to airports, not to mention the adverse impact of flying on our planet's climate.

Over the past three years, I have focused on the question what can be done to reduce aircraft noise in such areas. This dissertation presents the findings of this journey and shows that architectural and urban design can make strides forward in improving the quality of soundscapes exposed to aircraft noise. Moreover, the results could help airports and governments to amend and improve noise abatement strategies. However, in my opinion, the findings should not be simplified to a dull argument to legitimize the expansion of air traffic without further debate and scrutiny. Neither will the results lose their credibility and applicability if the number of air traffic movements would stabilize or fall. In the first place, I hope that the research will be used in good faith, with the intention to serve the interests of those who face the negative side of air traffic day by day. Secondly, I hope that the research will contribute to the quality of life in airport regions.

Finally, I declare that this dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and acknowledgements. The work in this thesis is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. The dissertation does not exceed the prescribed word limit for the relevant Degree Committee.

Cambridge, 7 December 2018

Nomenclature

SPL	sound pressure level in dB
OASPL	overall A-weighted sound pressure level in dB(A)
1/3-OB	1/3-octave band
p	air pressure in Pa
p_{ref}	reference air pressure ($2 \cdot 10^{-5}$ Pa)
L_{den}	sound pressure level day-evening-night, European noise metric
L_{max}	maximum sound pressure level in dB
L_{eq}	equivalent sound pressure level in dB
L_{Amax}	A-weighted maximum sound pressure level in dB(A)
L_{Aeq}	A-weighted equivalent sound pressure level in dB(A)
L_{A50}	median A-weighted sound pressure level in dB(A) (i.e. based on dB(A) levels, not the sound pressure)
SEL	Sound Exposure Level
IL	Insertion Loss in dB
FFT	Fast Fourier Transform
NPD	Noise Power Distance
ADS-B	Automatic Dependent Surveillance-Broadcast
VCNS	Virtual Community Noise Simulator
ICAO	International Civil Aviation Organization
FAA	Federal Aviation Administration
ECAC	European Civil Aviation Conference
INM	Integrated Noise Model (FAA's aircraft noise prediction model)
doc.29	document 29 (ECAC's aircraft noise prediction model)
*n*LOS	building side facing away from the flight path (no line of sight)
*d*LOS	building side towards the flight path (direct line of sight)
shielded facade	see *n*LOS (interchangeable)
exposed facade	see *d*LOS (interchangeable)
AAS	Amsterdam Airport Schiphol
NLR	Netherlands Aerospace Centre

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introduction

1. Introduction and research outline

1.1. Prologue

A regular day in July, 7am in the morning, our location is a meadow near the village of Zwanenburg just about a mile west of Amsterdam. The sun has just risen less than an hour ago and the first rays of sunlight heat the silver glaze of the morning dew covering the fields. The air has a crisp, sharp clarity, the sky is clear of clouds and filled with the smell of lush grass and hay pollen. Suddenly the tranquillity is interrupted by a distant and fast approaching whistle-tune, followed by a soft rumble. From behind the trees an aircraft navigates smoothly towards the nearby runway a few hundred yards away, to deliver freight and passengers at their destination. Soon a second and a third aircraft will follow, ushering an ongoing flow of airplanes descending to the runway. After the airport has distributed and digested all the incoming flights, it is time to repeat the same procedure in opposite direction. But by the time the first airship has moored at one of Amsterdam Schiphol's gates, the first noise-related complaints of the day will have been filed. Although the Dutch file more noise complaints compared to their neighbours, the situation is not just anecdotal for Amsterdam or the Netherlands. In fact, this situation is daily practice for large airports such as Heathrow, Frankfurt, Paris, Zurich, Vienna, Sydney and so on.

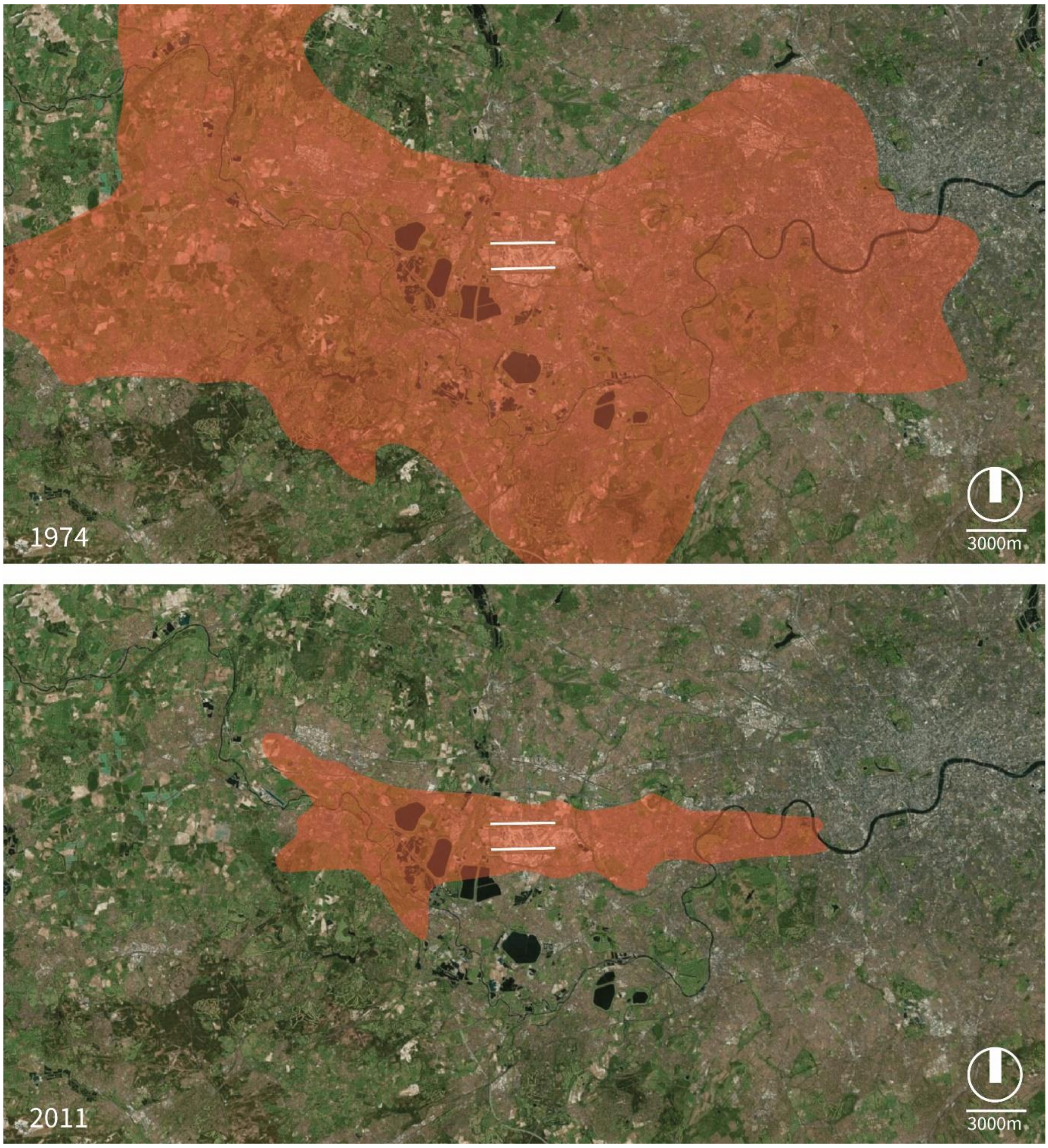

Figure 1 Noise impact of air traffic around Heathrow airport measured as the total area with average noise levels above 57dB (in red)[1].

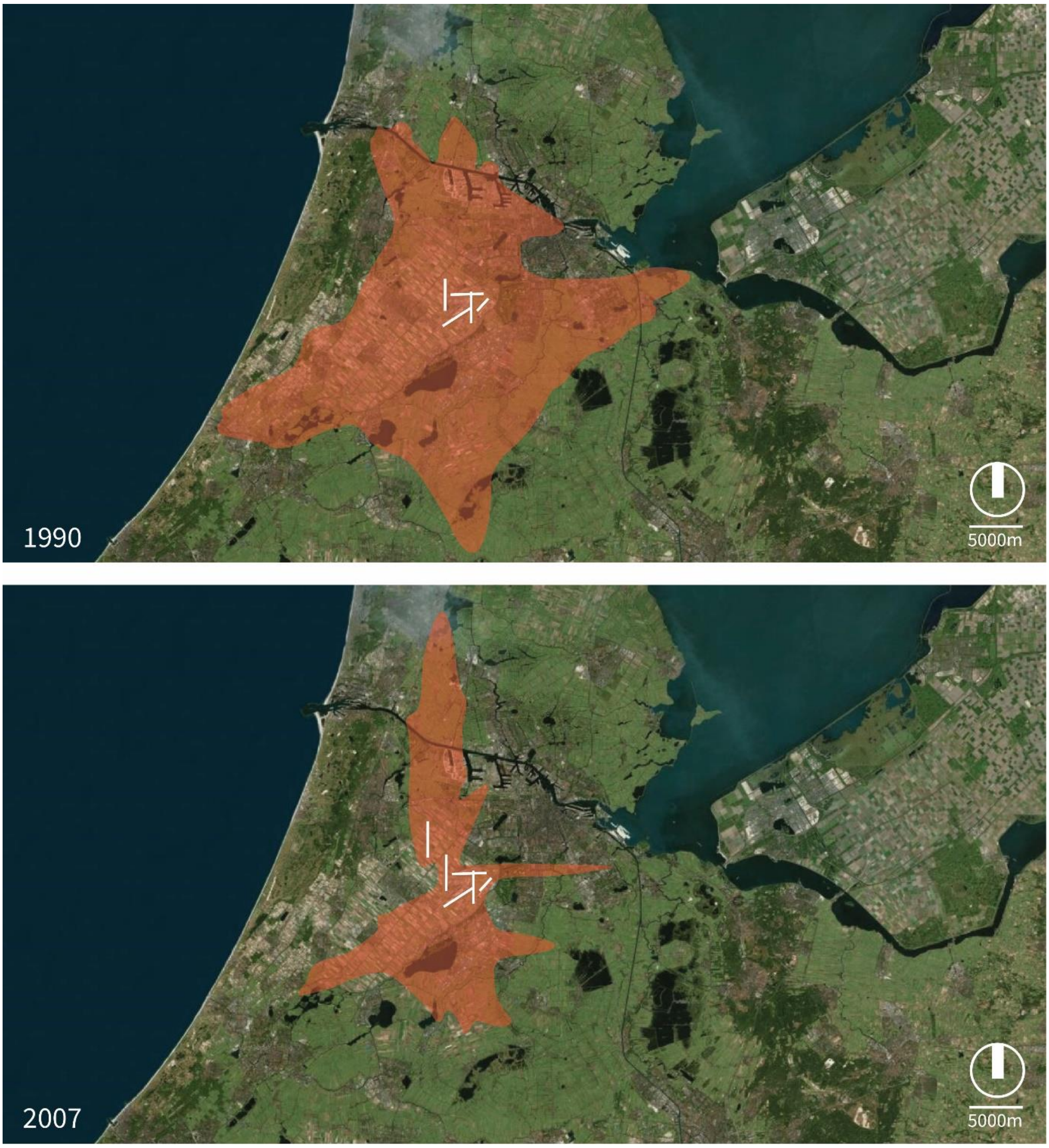

Figure 2 Average sound pressure level around Amsterdam Schiphol airport in 1990 and 2007 (in red: levels above 53dB Lden)[2].

1.2. Introduction

1.2.1. Air traffic and cities

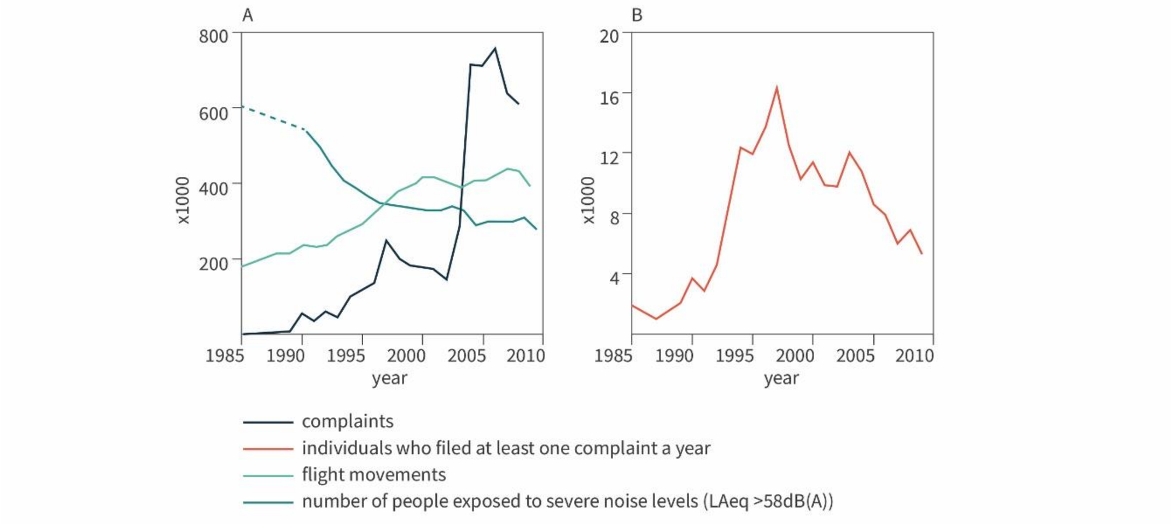

Figure 3 Complaints about aircraft noise around Amsterdam Airport Schiphol[2,3].

Aircraft noise causes a serious problem for airport authorities and governments. Around London, concerns about the noise impact of Heathrow's third runway sparked fierce debate in (British) parliament. According to the World Health Organisation 'excessive noise seriously harms human health and interferes with people's daily activities at school, at work, at home and during leisure time. It can disturb sleep, cause cardiovascular and psychophysiological effects, reduce performance and provoke annoyance responses and changes in social behaviour'[4]. For these reasons, airports must abide noise regulations imposed by government, and noise abatement and community engagement schemes have been rolled out. ICAO, the UN's civil aviation agency, compiled the most important noise abatement strategies in the balanced approached, which forms the international guideline for noise control around airport[5,6]. On the land side, noise contours prevent building developments in the proximity of flight paths and runways, while house owners have been compensated, e.g. in the form of extra acoustic insulation[6]. On the air side, quieter airplanes, optimized routes and adjusted flight procedures have reduced noise emissions[6]. And not without successes, as can be seen in Figure 1 and Figure 2. In terms of the equivalent sound exposure levels, the maps and charts show the staggering progress that have been made over the past decades.

1.2.2. Aircraft noise annoyance

But, despite all efforts, the number of complaints about aircraft noise hasn't dropped accordingly (see e.g. [2,7]). Instead, the numbers for Amsterdam show an opposite trend, which repeatedly ignites debate about curtailing further growth of air traffic in the Netherlands (see Figure 3). Based on literature, there are a few ways to explain the observed juxtaposition. Firstly, the relationship between the sound exposure level and annoyance is less static than assumed[8]. For example, the equivalent sound pressure level (Leq), i.e. the metric used for noise maps, only predicts a small proportion of the variance in annoyance levels[9–11]. Instead, non-acoustic factors, such as the attitude towards air traffic and the airport authorities, and the perception of coping are more important than acoustic factors[10–12]. Moreover, research shows that the dose-effect relationship between annoyance and aircraft noise varies over time and between airports[8]. Studies carried out for the same airport but in different years have shown significant differences. Other studies showed that the attitude to air traffic and aircraft noise are not independent from the way both issues are addressed in society, referring to the social-political discourse which shapes the public opnion[13,14]. Secondly, other acoustic factors seem more adequate to predict annoyance than the equivalent exposure level in an area[15]. For example, the number of flyovers and the maximum sound level during a flyover are better predictors than the Leq to explain the level of annoyance[15]. Thirdly, studies show that the level of annoyance depends on the location (indoors versus outdoors) of people at the time of exposure and the time of the day. In respect to the local context, also factors such as the satisfaction with a neighbourhood, place and dwelling affects the level of annoyance[15,16].

1.2.3. Noise, place and perception

The importance of perception, place and localized sound levels to predict noise annoyance does not only apply for aircraft noise, but for traffic noise in general. Hence, the impact of sound exposure, relative to the character of places in cities, has become more important in research on traffic noise in cities[17]. For example, various studies focused on the impact of buildings and streets to reduce sound levels locally[17,18]. Today, many European cities included the access to quiet building sides in municipal noise abatement schemes[18,19]. A quiet side can refer to a facade without direct exposure to a noise source and sound levels <45dB(A)[20]. However, it can also refer to facades that are more than 10dB(A) quieter than the facade which is facing towards the noise source, i.e. a road[21]. The design of buildings, roofs and facades can contribute to reaching such levels[18,22]. Other studies showed that natural features in cities can also reduce noise annoyance[23]. For example, the sight of vegetation from dwellings decreases the level of noise annoyance people reported[24,25]. Access to green areas near dwellings in areas with a high sound exposure level on the facades can yield a similar effect[26]. The effects of (visible) vegetation are estimated to an equivalent reduction of 10dB[23]. Also, the presence of natural sounds showed to improve the auditory quality of outdoor spaces exposed to road traffic noise[27–29]. Enhancing bird song through landscape architecture, or placing water features, are examples of urban design interventions suggested by researchers in several studies[29–31]. Like landscapes, the acoustic environment depends on the design of the (urban) context around people. Consequently, the soundscape is the combination of (a) sound(s), in a given (visual) context, which evoke(s) an immersive experience and an emotional response[32]. The examples show that, to some extent, urban and architectural design can influence the experience and response.

1.2.4. Design of the urban soundscape

These examples raise the question if the design of cities can play a role in the reduction of aircraft noise and improve the auditory quality of areas near airports. Regarding the perception of sound and cities, to the author's best knowledge, there are no studies on the effects of e.g. natural features in relation to the perception of aircraft noise. A few studies show that urban design and land use planning can be used to reduce aircraft noise. For example, the porosity of the soil near runways can be used to absorb aircraft noise during take-offs[33]. But, from an acoustic perspective, buildings hardly reduce or amend the level of aircraft noise when located close to perpendicular underneath flight paths[34,35]. However, for sites at a greater horizontal distance to the ground track of a flight path, studies suggest that buildings do have an impact on the sound levels of aircraft noise[36,37]. A study near Frankfurt showed a difference up to 7dB between two positions around a building during an aircraft flyover[37]. The same study showed a reduction of sound levels in front of a building exposed to aircraft noise, based on varying the facade design[38]. A computational study found a difference up to 5dB between low-density urban areas with varying urban morphologies exposed to noise from a low flying aircraft[36]. However, as the study focused on the urban macroscale, the influence of architectural design variables on the local sound pressure level around buildings was not studied.

1.2.5. Sound propagation models

Acoustic numerical models are often used to study the impact of architectural and urban design in relation to the local abatement of traffic noise[18,39]. Numerical simulation models are relatively cheap and convenient platforms to compare the effects of many design interventions under the same conditions. Since computers have become faster, a variety of numerical computer-aided models have been developed, ranging in complexity, speed and accuracy. Whether a model is appropriate depends on a project's scale and objectives[17,18]. Although some simulation packages developed tools to predict aircraft noise for areas around airports, the models only implement standard aircraft noise prediction methods[40,41]. These methods, such as doc.29 and INM, calculate the dispersion of aircraft noise around airports based on the noise footprints of individual aircraft types[42–44]. The data is based on measurements and corrected for e.g. meteorological effects and ground reflections[39,44]. The combination of flight settings, airplane types, engines models and flight routes generate bespoke noise footprints around airports[44,45]. The average sound pressure level in an area is predicated based on the cumulative effects of all flight movements during a specified period in time. However, aircraft noise prediction models omit buildings. Other, higher-fidelity, noise prediction models, used for e.g. noise aurilization, have the same limitation[44]. The means that it is currently not possible to study the impact of buildings, or architectural design variables, on the propagation of aircraft noise around buildings, without further research. Although urban acoustic simulation models can predict the sound dispersion around buildings, it is unclear to what extent the models can be applied for aircraft noise. A key issue is the role of atmospheric refraction on the propagation of aircraft noise, which is currently omitted in studies on aircraft noise and buildings. These questions restrict researchers to systematically study the effects of architectural and urban design on the local propagation of aircraft noise. Moreover, it also limits architects, urban planners and designers to test the impact of design proposals in relation to aircraft noise exposure.

1.3. Research framework

1.3.1. Problem definition

The design of cities, buildings and public spaces can reduce the exposure to noise or evoke a positive perception of the auditory environment. So far, research has mainly focused on noise abatement, or the noise perception, of urban design in relation to road traffic noise. The outcomes have helped architects, city planners and policy makers to improve and refine noise abatement strategies. However, yet there is no such equivalent for the relation between urban design and aircraft noise. Although literature shows that urban design in areas underneath flight paths hardly amplify or abate the noise, this is different for areas at a greater horizontal distance from flight paths. However, for such areas, there are no examples of systematic research on the noise abating effects of buildings exposed to noise dispersed by flying aircraft, apart from a few smaller studies. Acoustic simulation models can either predict aircraft noise, omitting the effects of buildings, or predict the sound propagation around buildings, but only for sources close to the ground surfaces (e.g. cars and trains). This means that it is unclear to what extent urban acoustic simulation models are applicable to study the propagation of aircraft noise around and between buildings. Also, in respect to the influence of natural features on the perception of aircraft noise, there is yet no published research. Research in both directions could benefit residents, design practitioners, policy-makers and airports.

1.3.2. Research gaps

In short, in relation to urban design and aircraft noise, there are three directions in which more research is required.

Firstly, literature on the noise abating potential of buildings exposed to aircraft noise is limited, especially for areas at greater distance from (a) flight path(s). The current body of literature shows a gap or blind spot, both in terms of empirical and numerical data. Hence, it is unclear whether building design variables, such as building geometry and urban density, influence the propagation and attenuation of aircraft noise.

Secondly, computational models, used to predict and calculate aircraft noise, neglect buildings, while urban acoustic models lack validated methods to simulate aircraft flyovers. This results in a grey area between both fields. As computational calculation methods are more efficient and viable ways to study the impact of building design on sound, research on intermediates between urban acoustic and aircraft predicting models could support soundscape research and design practice.

Thirdly, to the author’s best knowledge, yet no studies on the effects of natural visual and auditory features and soundscapes exposed to aircraft noise have been published. A growing body of literature have shown the potential of urban greenery and added natural sounds to reduce annoyance experienced from traffic noise. However, the existing literature only covers road and rail traffic sources, while the application of the results to fight aircraft noise annoyance are uncertain. This leaves the question to what extent natural features can improve the soundscape quality in areas exposed to aircraft noise.

1.3.3. Research objectives

Based on the three research gaps, the following research objectives were formulated for the doctoral research:

1. To study the noise attenuating potential of buildings exposed to aircraft noise in relation to the position of an aircraft and a receiver.
2. To study the application of numerical models to predict the propagation of aircraft noise around buildings.
3. To study the impact of the building geometry and surface properties on the level of aircraft noise around buildings.
4. To study the impact of the visual and auditory (urban) environment in relation to the perception and masking of aircraft noise.

The three objectives lead to the fourth overarching goal of the doctoral research:

- To develop tools that can support architects, urban designers and planners to reduce noise exposure and improve the soundscape quality in urban areas near airports.

1.3.4. Research questions

The research gaps and the objectives lead to the following main research question:

> *How can urban and architectural design reduce aircraft noise and improve the soundscape quality for areas exposed to aircraft noise?*

The main question was studied by means of four sub questions:

1. *To what extent do buildings reduce aircraft noise in areas that are not directly underneath flight paths as the distance between the aircraft and a receiver increases? (Studied in chapter 5)*

2. *To what extent can urban acoustic models predict aircraft noise around buildings with an acceptable accuracy without considering atmospheric effects? (Studied in chapter 6)*
3. *To what extent can the design of buildings and street canyons improve the reduction of aircraft noise locally within areas that are not directly underneath flight paths? (Studied in chapter 7)*
4. *To what extent can visual and auditory natural features improve the soundscape quality of urban areas exposed to aircraft noise? (Studied in chapter 8)*

These four questions are studied by means of various research methodologies, ranging between (in-situ) measurements, numerical acoustic computation and (virtual reality) lab-human-subjects based research. For the readability of the thesis, each chapter will address one question and introduce the relevant literature first. Figure 4 shows the structure of the thesis and the links between the individual chapters.

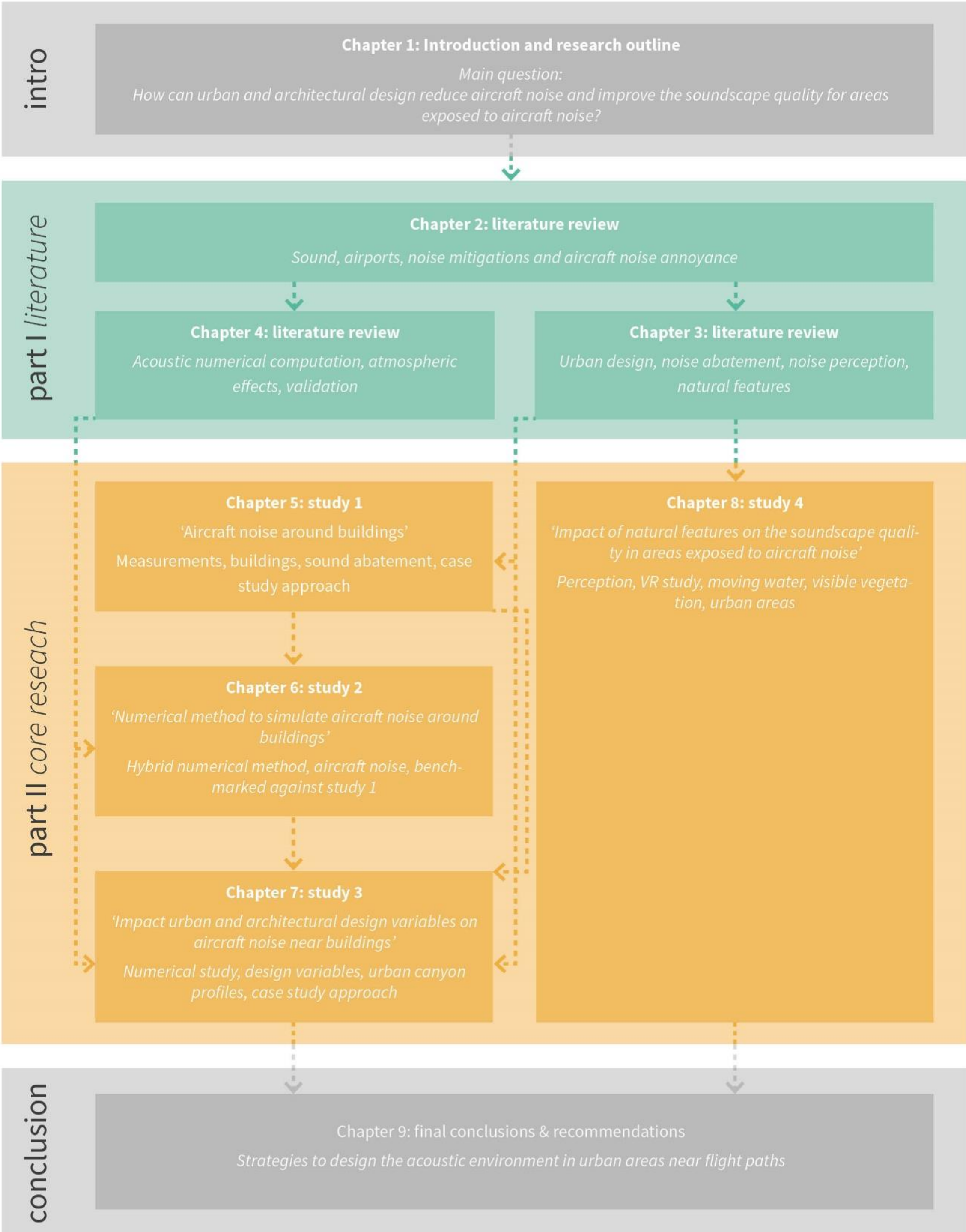

Figure 4 Research outline with the sequence and links between the indiviudal chapters and topics.

1.3.5. Scope of the research

Aside from the academic objectives, the impetus of the research was to develop tools that can help architects, urban planners and designers to improve their designs for outdoor areas exposed to aircraft noise. More specifically, the research focused on a design toolkit to complement design practitioners during the initial and probationary phases of (urban) design projects. Although airplanes disperse noise when taxiing and engine run-ups as well, the research only focused the noise emitted during aircraft flyovers. The doctoral research covered two areas: 1) acoustic and 2) perception-based research. This also means that that focus of the research adopts a broad scope, aiming to study interventions in both directions. Inherently, this means that the research intended to set the beacons for further research in both directions, based on the results of the doctoral research. The research approach has two limitations. Firstly, the research often examined how existing theories and methods can be harnessed for a different sound source, namely airplanes. Secondly, the variety of studies also limited the time that could be spend per theme or topic. Hence, if a study led to follow-up questions, it was not always possible to set up follow-up experiments, or to validate results by means of more detailed models. This means that the studies led to several questions and/or suggestions for future research, which are presented and discussed in the final chapter.

1.4. Structure of the research and thesis

1.4.1. Structure of the research

The thesis consists of three literature and four research chapters. Before the experiments were designed and the data collection was started, an extensive literature research was carried out. The literature chapters provide a theoretical and methodological framework for the four studies. Although the fours studies can be read individually, they are connected in terms of e.g. the case study locations (chapters 5-7), or the way a study contribute to the overall research objective(s) (chapter 8). Figure 4 shows the links between the chapters and the overall research outline. The core research chapters are written in the style of (scientific) journal articles, each covering one topic per chapter. As chapters 5-7 are successive, the intention is to submit the other chapters once chapter 5 has been accepted and published.

1.4.2. Research methods

The doctoral research comprises four studies in which different research methodologies were used. Since each study covers a different issue, a detailed description of the relevant research methods is given per study, presented in the chapters 5-8. To give an impression of the consistency between the research chapters, the research methodologies and reciprocities between the studies are discussed at a glance.

To study the first research objective, the doctoral research commenced with a study in which the abatement of aircraft noise by buildings was examined, based on measurements. Data was collected around several buildings at three locations near one of Amsterdam Airport Schiphol’s runways. Resources and equipment were provided by the courtesy of the Dutch Aerospace Centre (NLR from now on), which was also one of the funding partners behind the research. Dutch Air Traffic Control (LVNL from now on) granted permission to use aircraft positional data within the context of this research. The data from the measurements also provided three benchmark cases for the second study. This study put the focus on the development of a numerical method to simulate aircraft noise propagation around buildings. To bridge the gap between aircraft noise prediction and urban acoustic (numerical) models, an intermediate approach was developed and tested. Numerical results were compared to a reference study, but also benchmarked against the measurements. Subsequently, the intermediate numerical method was used to analyse the influence of architectural design variables in relation to aircraft noise abatement in a third study. The impact of individual and combined variables was calculated for the same case study locations as used for the previous studies. In the fourth study, NLR's virtual community noise simulator (VCNS) was used to compare the influence of natural features in urban environments exposed to aircraft noise. By means of a lab experiment, it was tested to what extent natural features yielded an effect on the perception of the soundscape quality in urban areas exposed to aircraft noise. Hence, the VCNS was used to create virtual environments comprising videos and animations that gave a realistic and immersive impression of aircraft noise and environments. The VCNS was used in previous studies and lends itself for perception-based research. Finally, the results from the four studies were used to answer the central research question.

1.4.3. Reading guide

The literature and research chapters are written in a different style. The literature chapters present the relevant literature in a subsequent order without conclusions (but with a summary at the end). The research chapters are written in the form of journal papers, with each chapter covering a separate study. The argument of the doctoral thesis is formed by the sequence of the studies, covered in the literature and research chapters. Apart from the literature chapters, each chapter starts with an abstract, short introduction, relevant literature (if needed), results and conclusions.

All written work is from the author's hand, although co-authors and fellow researchers supported the research through ideas and feedback. Co-authors are mentioned in the relevant chapters. Where needed, the collaboration, funding and input from others is discussed in Appendix A in more length.

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part I *literature*

2. Noise, air traffic and annoyance

The response to road, rail and air traffic noise depends on the sound signal and its reception. Although it starts with an acoustic pulse, sound becomes noise once the brain has given a meaning to it. In this chapter, the concepts behind aircraft noise, airports and annoyance, forming four themes, are introduced and discussed. Firstly, the physical bases of sound and outdoor sound propagation are introduced. The chapter discusses only those concepts that are relevant for the doctoral research, and more information can be found in handbooks and literature. Secondly, the chapter describes the concepts behind traffic and aircraft noise. Thirdly, the chapter dedicates a section to the impact of aircraft noise on cities, and the current state of aircraft design and future innovations. The section also focuses on the mitigation of aircraft noise by means of land and air-side measures, and the relationship between exposure and response. The fourth section elaborates on the theme of aircraft noise annoyance, referring to recent developments in this field. The final section extends the scope to the perception of (aircraft) noise in relation to the environment people are in.

2.1. Sound

Sound waves are vibrations moving through a medium. The vibrations destabilize the equilibrium of the energy which keeps particles in place, resulting in wave-like density differences. Although sound can move through any medium, in the context of this thesis, sound refers to the pressure fluctuations in air. The length of a wave depends on the motion of the sound source, and the force or the thrust that defines the magnitude of the energy compressed in a wave. Waves can propagate from a point (i.e. spreading out spherically in all directions), a plane (i.e. with wave fronts infinitely parallel to each other) or a line[1]. A sequence of point sources becomes a line source, while small segments of spherical waves can be approximated as plane waves if the distance from the source is large enough.

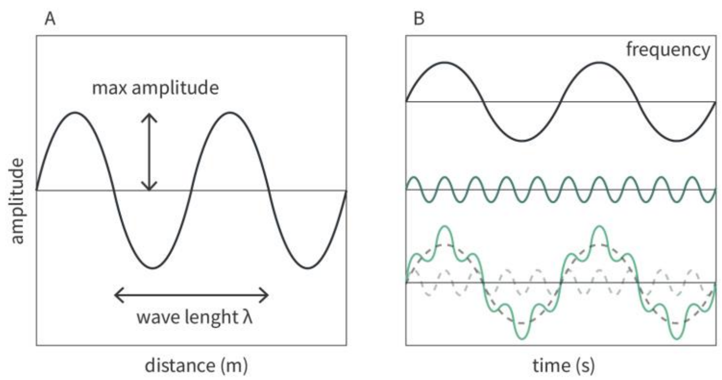

Figure 5 a) wave length and amplitude, b) wave formed of multiple frequencies.

Figure 5a illustrates the length and amplitude of a wave, i.e. the magnitude of energy compressed in a wave. Often, sound is expressed by the frequency and loudness of (a) wave(s). The frequency is the number of waves per time unit (often one second) and depends on the speed of sound in a particular medium, which is around 344 m/s for air (ie. near the ground surface in an outdoor temperature of 20°C). The sound pressure level is expressed on a logarithmic scale in decibels (dB), based on the air pressure. The human ear is only sensitive to a small range of frequencies, i.e. those between approximately 20Hz and 20000Hz. Although frequencies lower than 20Hz, if loud enough, can be felt as vibrations, most people cannot hear such tones. Unless a source emits harmonic waves, i.e. a single frequency, sound often comprises multiple frequencies (see Figure 5b).

2.1.1. Sound audibility and decay

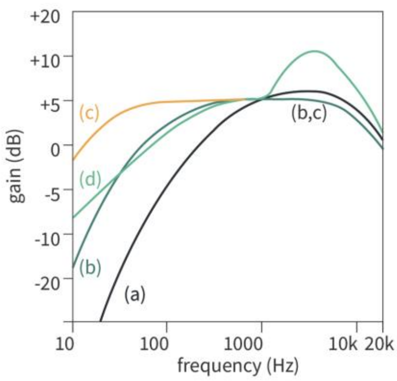

Figure 6 Human sensitivity to sound and scales needed to correct the loudness accordingly (A, B and C weightings).

As with the frequency domain, there is also a minimum human hearing threshold for sound, which increases with age, and varies between frequencies[2]. In general, tones within the speech domain, i.e. frequencies between ≈200Hz and ≈5000Hz, are heard clearer than tones below or above these frequencies[1,2]. Practically, this means that tones with frequencies outside the speech domain must be louder to be perceived as being equally loud to frequencies falling within the speech domain. To balance the loudness perception for different frequencies, various correction scales have been introduced over the last decades (see Figure 6). The A-weighting is the most common correction used for traffic and aircraft noise[1,3].

Spherical waves emit sound energy in all directions. Due to the law of conservation of energy, the loudness of a sound wave will decrease as the distance from the source greatens, as the energy is increasingly distributed over a larger area[1]. Further damping is caused by the friction and resistance of air particles, which partly convert the sound energy to heat. The extent to which air absorbs sound depends on the frequency, i.e. the absorption increases for higher frequencies. Unless a source produces a constant and continuous motion, the sound it emits is temporary and will fade away once the particles resettle in the initial pressure equilibrium.

2.1.2. Reflection, absorption, transmission and diffraction

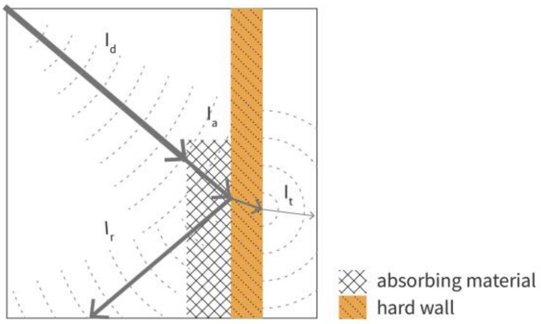

Figure 7 Reflection (I_r), absorption (I_a) and transmission (I_t) of sound against surfaces.

Along the propagation path, the direction and intensity of sound is often influenced by obstacles and surfaces. Vertical (ground) and horizontal (barriers) surfaces reflect, absorb or transmit the sound, as shown in Figure 7. The level of absorption and transmission depend on the angle of incidence θ, the material and the frequency[1,3]. Transmission through walls means that the sound waves will propagate into the interior of buildings, which can be reduced or blocked by the mass and stiffness of the wall's material. Acoustic absorbing materials partially convert the sound energy into heat through friction in the pores[1,3]. The level of absorption can be expressed by three metrics: 1) the absorption coefficient, 2) the impedance and 3) the flow resistivity.

Compared to the other metrics, the acoustic absorption coefficient is a more generic approach to quantifying the absorption, e.g. suitable in cases where the sound field is diffuse with random incidence. Although the coefficient can be defined for each angle, this requires a significant amount of work and experiments, and instead, it is common to use a single number for all angles. Hence, the absorption coefficient is sufficiently accurate if the angle of incidence is of lesser importance. The acoustic absorption is expressed as a value between 0 (no absorption) and 1 (full absorption). However, the impedance and flow resistivity describe the acoustic properties of materials more precisely. The impedance of a surface relates to the absorption coefficient, the angle at which a wave hits a surface and the bulk density of the material (pressure)[1]. The acoustic impedance is expressed by the unit Z, which is a complex number[3]. For porous composites, i.e. materials comprising a porous or permeable material on top of a hard layer, the flow resistivity is often used instead of the impedance[3]. To calculate the flow resistivity, both the impedance and the thickness of (an) additive(porous) material(s) are considered. The flow resistivity describes the level of resistance air encounters when it moves through the material. The metric is expressed in units of $kPa \cdot s \cdot m^{-2}$ [3]. Examples of composite materials are snow or mulch on top of a hard ground, although more seemingly homogeneous materials, such as grass and concrete, can also be described as 'porous' mediums[3].

Unless a surface material absorbs an incident sound wave entirely, at least a part of the energy is reflected. If the sound is reflected in the direction of the receiver, and if the path is clear of other obstacles, the reflected part of the wave will reach the receiver moments after the direct wave has arrived. If a source emits more than one pulse, the combined direct and indirect waves may amplify or cancel the sound level that reaches a receiver. Consequently, direct and reflected waves moving in opposite phase can lead to interference, which can also create passive or active anti-noise[3,4].

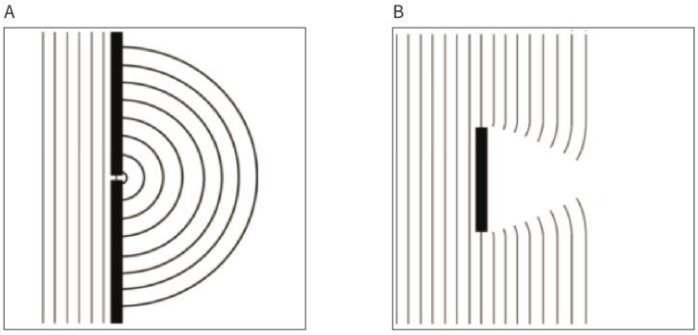

Figure 8 Edge diffraction of waves moving around a small gap (A) or a larger obstacle (B).

Vertical surfaces reflect, absorb or transmit incident sound waves, like horizontal planes. However, because sound's character is that of a wave, vertical surfaces also diffract the wave near the edges of the obstacle (see Figure 8)[1]. The wave will bend on the obstacle edge, which changes the direction of the wave front and curves the form of the wave[1,3,5]. Practically, this means that sound still reaches the area behind the vertical obstacle, thus diminishing the shielding effect of barriers. Consequently, the design and materialization of the edge of a building or barrier is important for the noise reduction behind the structure.

2.1.3. Sound in outdoor areas

In contrast to the air in confined indoor spaces, the air in outdoor environments is less stable and homogenous. Because sound depends on the propagation medium or fluid, this means that fluctuations in the medium influence the path and the distribution of energy. The atmosphere is comprised of different layers with varying temperatures and wind speeds for each layer[3,5]. Like light waves, sound waves refract when they move through multiple fluids with different volumetric mass densities[5,6]. In the first instance, refraction changes the direction of the sound wave. However, variations in wind velocity and wind direction also decrease and/or accelerate the propagation speed of the waves[3].

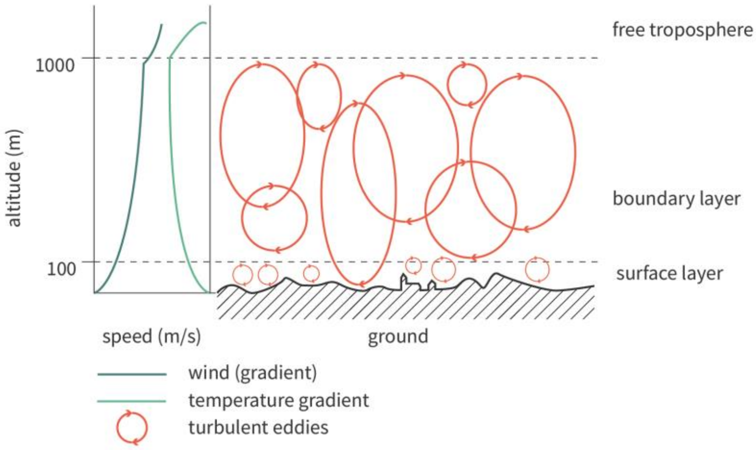

Figure 9 Wind and temperature profiles in the atmosphere, and turbulent eddy structures, adapted from [5].

Figure 9 illustrates the wind and temperature profiles in the atmosphere. In general, wind speed increases with the height (up to 1000m), whereas the opposite is true for the temperature gradient during daytime[5]. The gradient reverses during night time which is due to temperature differences between the sky (cooler) and the ground surface (warmer)[3,5]. As the air layer scrapes over the ground surface, the roughness of the surface generates local turbulent eddies[5]. Turbulence is also caused by sudden and local wind and temperature variations, scattering the sound waves if they move through such areas[5]. According to literature, turbulence plays only a minor role when a source and receiver are both located in the surface layer[3,5]. However, if the source is positioned in the boundary layer, which is the case for sources like (flying) airplanes and tall wind turbines, the sound can be affected by turbulence. For aircraft noise, literature shows that atmospheric turbulence can lead to spectral broadening, i.e. the distribution of tonal sound energy to other (surrounding) frequencies[7]. In some situations, this may cause differences between theoretical predications and measurements[6].

2.1.3.1. Up- and downwind propagation

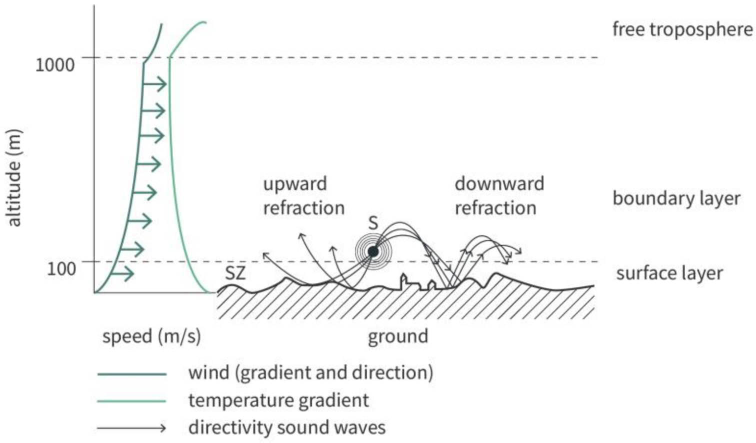

Figure 10 Up- and downwind refraction of sound waves around a sound source (S) in the atmosphere. SZ refers to the a refractive shadow zone.

The temperature and wind gradients in the atmosphere lead to up- or downwind refraction of sound waves (see Figure 10). During daytime and under normal weather conditions, receivers positioned behind a source, i.e. the area in line with the wind direction perpendicular to the source, are exposed to downward refracted sound. In general, wind effects are more dominant than the effects of temperature[5], which is why some methods to calculate atmospheric refraction omit temperature as a variable[5,6]. Up- and downwind refraction can increase or reduce the noise abating effects of barriers and buildings significantly due to the direction of the wave front. As illustrated in Figure 10, compared to a straight propagation profile, refraction changes the angle at which sound waves hit an obstacle. Subsequently, the direction of the wave front also affects other elements that depend on the angle of incidence such as edge diffraction, reflections and/or the absorption of surfaces. The next chapter will introduce the influence of refraction in more detail.

2.2. Traffic and aircraft noise

After the sound has reached the human ear and is processed by the brain, sound loses its physical objectivity and turns into a subjective noise. Literature shows that the appreciation of, or nuisance from, the sound depends on like e.g. the context, th source, the time of day, but also the personality of the receiver. However, acoustic characteristics, such as the loudness, sharpness, duration, spectrum, also predict the reaction that sound elicits, at least to some extent. Before the chapter introduces the interaction between sound, context and annoyance, traffic and aircraft noise are discussed in more depth.

2.2.1. Traffic and noise

Traffic noise can be broken down in three groups. The first group relates to the noise dispersed by cars, motorcycles, trams and bicycles. As the latter are relatively silent, cycles are usually omitted in traffic noise literature. The sources in the first group are all forms of urban transport in cities. The second group represents the noise from (high-speed) trains and wheeled vehicles that run on rail-tracks. Trains are usually studied separately from (urban) traffic sources, as are motorways. However, in many ways, the same principles apply for trains as for cars, motorcycles and trams. The third group comprises noise from aircraft traffic, which is introduced in the next section.

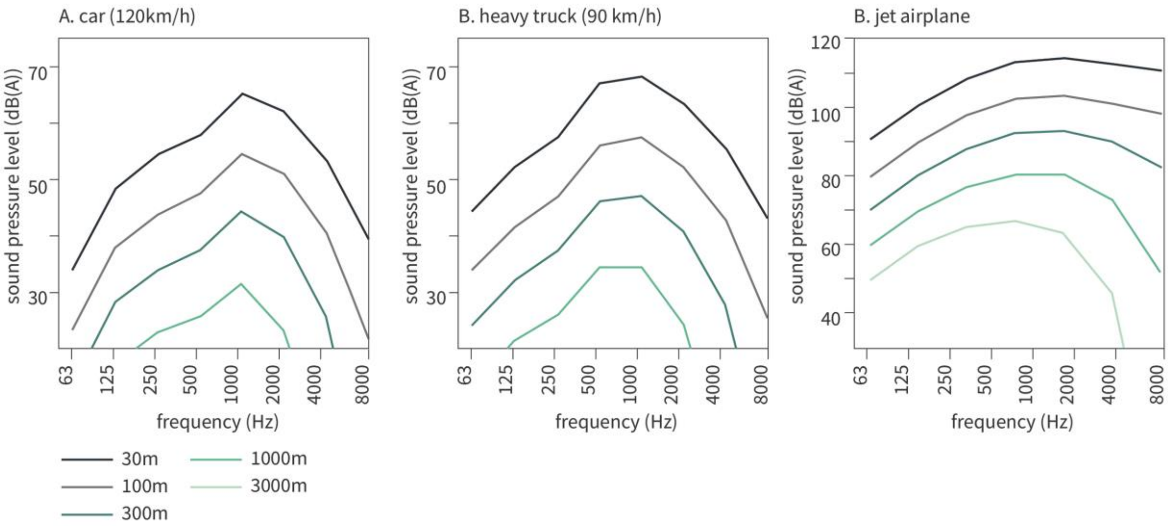

Figure 11 Sound spectrums of three traffic sources with an indication of the decay with distance, based on atmospheric absorption and spread[3].

In general, motorized sound sources are made up of the various individual elements that vibrate and produce sounds. The combustion of fuel in the engine produces a roaring sound, while the interaction between the tyres and pavement generate higher, creaking, pitches. In cities, the level of traffic noise will probably decrease in the future, as electric engines rely on magnetic fields rather than combustion, which make the engines quieter. However, a moving vehicle also creates friction between the surface of the vehicle and the surrounding air column, resulting in sound. For trams and trains, the contact between the wheels and the rails make vibrations travel through the soil to foundations and walls. This means that the vibrations can reach the inside of buildings in the form of more vibrations or sound. This is a major concern for building projects next to railways, but also for buildings near motorways, e.g. for buildings accommodating ultra-sensitive facilities like laboratories. The sound level and the spectrum of the source depend on the speed of the source. For example, the sound dispersed by the friction of tyres and road pavements, and the friction between the airframe and the air, increases with the velocity of the source[3,8].

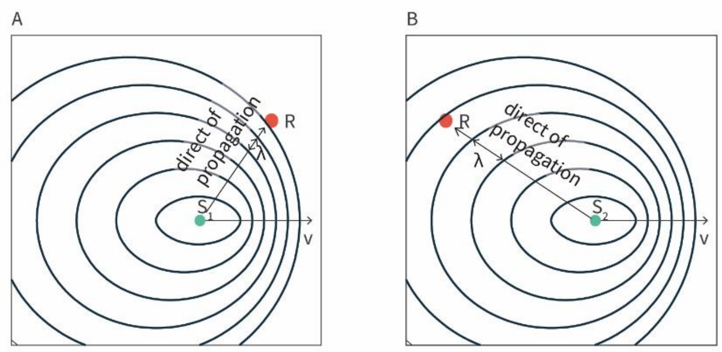

Figure 12 Doppler shifts in relation to the position of the source and a receiver. The position of the source S, in relation to the receiver R, changes as the source moves with a velocity v, changing the wave length (A, time = 1s, B, time = *n* + 1s).

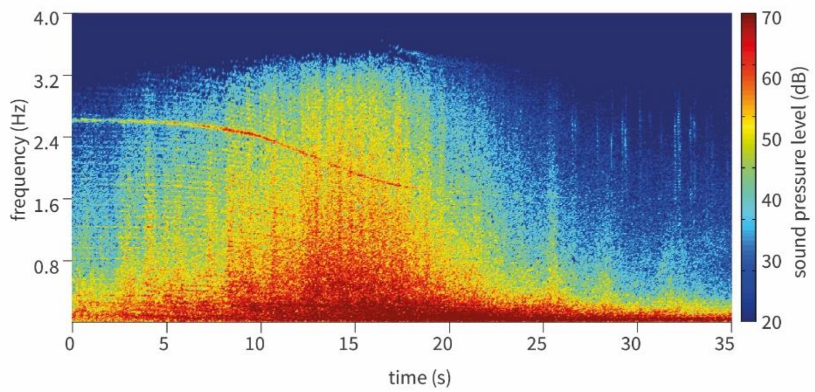

Figure 13 Spectrogram of an aircraft flyover with the Doppler effect clearly visible, adapted from [6].

Depending on the position of the source in relation to the receiver, the Doppler effect will change the frequency of the sound. This means that the wavelength shifts, depending on the position of the receiver (see Figure 12). The Doppler effect is visible in the spectrogram in Figure 13 as the horizontal bands that shift to lower frequencies over time.

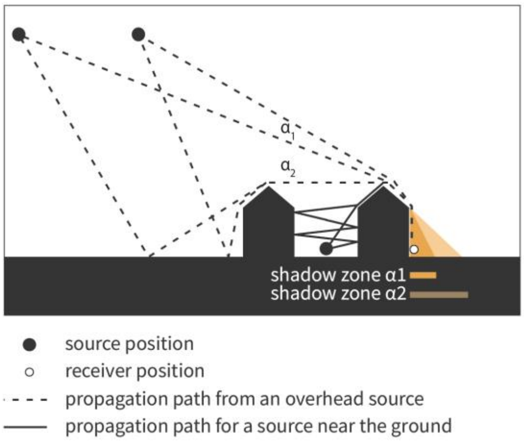

Figure 14 Sound dispersion from a source to a receiver position not directly facing the source (*n*LOS), for a situation where the source is close to the ground or up in the air. The dotted line is the shortest path from source to receiver.

Figure 11 illustrates the differences between airplanes, cars and trucks. Proportionally, aircraft contains more low frequency noise than cars and trucks. However, the most striking difference between airplanes and other traffic sources is the position of the source (see Figure 14). While buildings can generally prevent sound moving from a street to adjacent (court)yards, this is less straightforward for aircraft noise. Instead, for airplanes, the shielding potential of buildings depends on the horizontal (and vertical) distance between a building and the flight path[9,10]. The relationship between buildings and aircraft noise abatement is discussed in chapter 3.

2.2.2. Air traffic and noise

Although aircraft noise is mainly associated with the sound of flying airplanes, aircraft noise is emitted during different modes or working cycles. In total, the following eight modes are identified in literature ([11 p.4]):

1. 'starting engine operation
2. Pre-flight engine run
3. Taxiing to line up
4. Acceleration on the runway with full or reduced throttle
5. Take-off and roll-on
6. Flight path
7. Landing
8. Run-on operation and engine run-up' (e.g. for maintenance)'

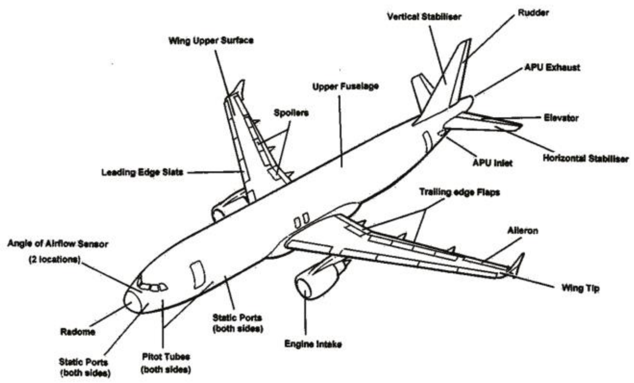

Figure 15 Different sound producing compontents of an aircraft.

These eight modes can be clustered in three groups, depending on the altitude and position of the aircraft in relation to the runway or platform:

- Noise dispersed by aircraft moving between the platform and the runway and in contact with the ground (numbers 1, 2, 3 and 4)
- Noise dispersed by aircraft moving on the runway or when stationery on the platform (numbers 5 and 8)
- Noise dispersed by fast moving aircraft which are off the ground (numbers 6 and 7)

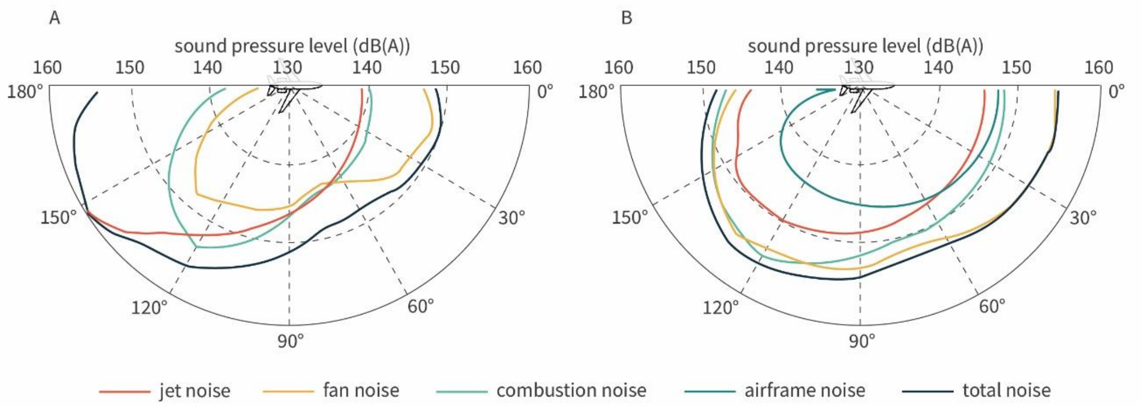

Figure 16 Aircraft noise with power setting during take-off (a), the aircraft is not moving, compared to an aircraft moving at Mach 0.25 (b) for different polar angles (see [6] p. 39-40).

Aircraft noise, as with other traffic sources, can be broken down into individual sound emitting elements. However, most of the sound comes from the tail plane, engine (jet, fan inlet, turbine), fuselage, wins, flaps, spoiler and nacelle[6,12]. To describe aircraft noise mathematically, the different sources are divided in four (noise) categories, and the combination of these four categories are used to e.g. synthesize aircraft noise. The four categories are 1) fan, 2) jet, 3) combustion and 4) airframe noise. For each category, there are different models that describe the sound emissions of individual categories[6], e.g. by Stone (jet noise)[13], Fink (airframe noise)[14] and Heidmann (fan noise)[15]. Figure 16 shows the sound profiles of the four models for two working cycles. The figure shows the differences in directivity and loudness between the various source categories. The figure also indicates the overall sound level and directivity, which is the combination of the separate models.

Depending on the position of a receiver and the working cycle, the sound directivity and the level of exposure will vary. For example, sound levels are particularly high during take-offs when the receiver is positioned behind the aircraft at an angle of between 30 to 40 degrees. The directivity profile of a flying aircraft shows that the sound energy is almost spherically distributed around the source (Figure 16b).Compared to engine run-ups and take-offs, taxiing airplanes are much quieter [11,16]. During a single event the sound level is the result of controllable factors such as the aircraft and engine types, and fluctuating variables such as the pilot settings and/or the weather. Literature shows that, for the same aircraft type, the sound levels as measured on the ground can deviate by as much as 12dB. Most of the variation is attributed to the source and pilot settings and not, in this case, to atmospheric fluctuations[17]. This means that the sound profile of individual flyovers can vary significantly, depending on the captain, freight and weather.

2.3. Airports and cities

Since the end of the Second World War, commercial aviation has taken off and transformed the way both goods and people get from A to B. Many modern airports, like Amsterdam Airport Schiphol and London Heathrow, were once military bases and located outside cities[18]. Incremental growth of cities and airports has reduced the distance between the two, thus exposing more people to aircraft noise. Often, buildings and infrastructure are needed around airports to facilitate the economic activity generated by air traffic[19,20]. Airports have thereby turned into regional economic powerhouses, creating jobs in the wider area around airports[19–21]. The airport city concept, as coined by Kasarda and Lindsay[19] and adopted by various large airports, is based on the idea that airports can catalyse and channel economic development. Kasarda and Lindsay advocate a strategy in which the connectivity and network and connectivity of an airport take an important position. A well-connected airport is attractive to global tertiary companies, which increases the demand for office space at, and around, the airport. Ultimately, this also boosts the demand for housing and infrastructure in the area around the airport.

The continuous process of economic push and pull initiated by airports, and the spatial consequences, is visible around many, more established, European, North-American and Asian airports. Since the legal formalization of noise abatement and urban planning instruments, such as noise contours, it has become easier to manage and oversee urban sprawl. However, there are various examples of airports that showcase the difficulty to govern or reverse urbanization near airports. In some cases, airports were relocated outside the city, but this did not stop some airlines from returning to the original airport years later (e.g. Montreal[22]), or lobbying to keep depreciated airports open (e.g. Berlin-

Tegel[23]). More recent cases in the Netherlands, Britain and Germany have shown the technical and political complexity to relocate airports. Since the 1990s, Dutch politicians and policy-makers have been discussing the possibility of moving Amsterdam Airport Schiphol to a new-to-build artificial island in the North Sea[24,25]. So far, the debate about this idea has ended in a financial and technical stalemate. A similar idea was endorsed by Boris Johnson for London, with his plan to replace the London airports with a brand-new airport in the Thames estuary[26,27]. The initial plan originated from the 1940s and was finally voted down in favour of a third runway for Heathrow airport in 2015[27,28]. In Berlin, plans for a new airport to replace the two former East and West German airports date back to the years after the fall of the Berlin Wall, although it would take another twenty years before the construction works commenced. However, the project has backfired financially and technically, with an empty airport and huge cost overruns as the current result[29,30].

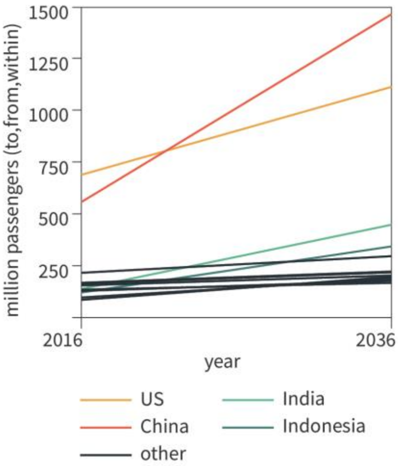

Figure 17 Prognosis for air traffic by IATA[31].

In respect to the complex reciprocity between airports and cities, history seems to repeat itself in countries going through a rapid economic growth, followed by a growing middle class, as already seen in Western Europe and North America many decades ago. On a global scale, IATA foresees air traffic continuing to grow, at least until 2030, which will increase the number of flight movements and the emissions (see Figure 17)[31]. In countries like China, Columbia, India and Turkey, the combination of abundant urbanization and weaker legislative restrictions for airports may have already sown the seeds for future disputes between airports, government and citizens.

2.3.1. Developments in air traffic and emissions

Aviation leads to noise and particulate emissions. After combustion, the exhaust gasses are dispersed in the sky in the form of CO2, NOX, H2O and (ultra) particulates. Various studies have reported on the concentration of particulates around airports and the potential adverse health effects[32,33]. As introduced in section 2.2.2, aircraft noise is the combination of the sounds emitted by separate parts. Since the 1960s and 1970s, aircraft noise has been an issue for airports and policy makers[18,19]. The introduction of the fan engine during the 1960s resulted in higher noise levels, followed by a burgeoning of civil groups stepping up the protests against airport expansion[18,19]. In order to reduce noise exposure and emissions, industry, airlines, airport authorities and government joined forces, resulting in a significant reduction of noise emissions.

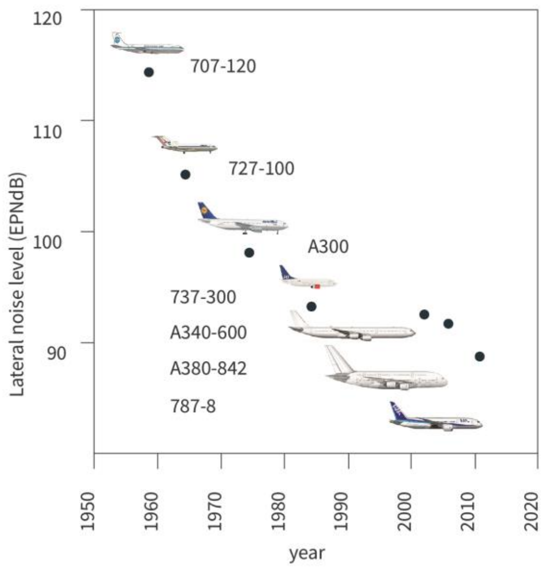

Figure 18 The reduction of noise emissions between the 1970s and 2010s[34].

Figure 18 shows the noise emissions for various airplanes between the 1950s and 2020. Modern aircraft are significantly quieter, based on research that resulted in better designs. However, the figure suggests that most big gains have already been implemented, and the impact of additional noise reducing features is expected to be relatively small by comparison. Although innovations like the single-wing design and electric engines could reshape the picture of flying in the future, it will take decades before such innovations are rolled out and implemented[35,36]. Annual reports by Easyjet, Air France-KLM and Lufthansa show that the life time and depreciation of new airplanes lie between 20 and 25 years[37,38]. This means that airplanes assembled by Boeing, Airbus or Embraer today are considered to remain operational for decades after leaving the factories. Also, a lower noise footprint per flight would not reduce the average sound exposure levels if outpaced by the increase in the number of flight movements. Finally, the urgency of carbon emission situation might skew the attention of industry and policy makers towards fuel efficiency in the foreseeable future, with noise concerns come second.

2.4. Aircraft noise abatement strategies

To protect citizens from annoyance and severe noise exposure, urban planning near airports is regulated by a variety of rules and restrictions. In many countries, noise contours form a legal basis to prohibit or limit building activities in specific areas[39]. In some countries, national legislation also regulates the size of water surfaces (i.e. to limit collisions between airplanes and birds) or imposes safety and hazard zones for areas close to runways[20]. Often, the equivalent sound pressure levels during day and night time form the acoustic basis underpinning the legislation. For example, the European Noise Directive talks about L_{day}, $L_{evening}$ and L_{night}, together making the L_{den} metric (day, evening, night, see equation below).

$$L_{den} = 10log\,\frac{1}{24}\left(12 \cdot 10^{\frac{L_{day}}{10}} + 4 \cdot 10^{\frac{L_{evening}+5}{10}} + 8 \cdot 10^{\frac{L_{night}+10}{10}}\right) \tag{2.1}$$

The equation awards penalty scores to noise events that take place during the evenings and nights. The L_{den} is the common unit for noise calculations for member states of the European Union. Different metrics are used in North America, such as the Community Noise Equivalent Level (CNEL) by the FAA[40] or NEF in Canada[41]. In general, aircraft noise metrics assume that a direct or indirect dose-effect relationship exists between sound exposure, annoyance and health. In other words, annoyance is the consequence of the equivalent sound exposure level. Hence, a higher equivalent sound exposure level leads to a higher annoyance response. Based on health and stress studies, maximum levels have been defined, which means that locations where the average sound levels surpass the maximum limit are unfit for human occupancy[42–46]. In the form of noise contours, the dose-effect relationship is also one of the bedrocks of the Balanced Approach to Aircraft Noise Management by the International Civil Aviation Organization (ICAO). The Balanced Approach combines a gamut of noise abating measures at different levels. Aircraft noise mitigations can be divided into airside and landside strategies. In this context, airside strategies focus on aircraft design, flight procedures and route optimization schemes. On the contrary, landside strategies deal with land-use planning, insulation and compensation schemes around airports. The Balanced Approach consists of the following four categories[47,48]:

1. Reduction of noise at source
2. Land-use planning and management
3. Noise abatement operational procedures
4. Operating restrictions

Noise contours, respite schemes (i.e. banning flight activity during the night) and continuous decent approaches (CDA)[1] are examples of strategies widely adopted by European and North American airports[39]. Respite schemes and CDAs are classic examples of airside strategies, while noise contours are landside measures.

[1] Landing procedure when the aircraft glides towards the runway and only uses the engines at lower thrust when necessary to steer to a different position or altitude.

2.4.1. Robustness of the dose-effect curves

The dose-effect relationship is a cross-disciplinary approach that links physics (acoustics) and behavioural sciences (psychology). In most cases, the relationship between sound exposure and annoyance is based on surveys and matched with the postcode of the respondents. Based on the results, the corresponding exposure level (either measured or calculated) is matched with the annoyance ratings from the survey[43,49]. Over the last decade, various studies have shown that dose-effect relationships can change over time[50,51]. This means that the percentage of people who indicate that they feel highly annoyed in relation to the sound exposure level, is not set in stone.

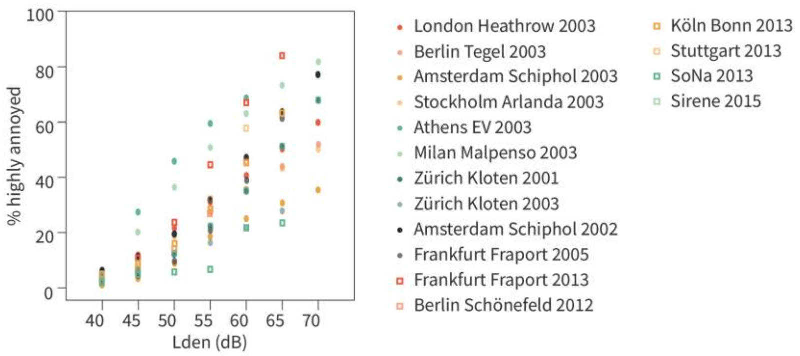

Figure 19 Comparison of different exposure-effect curves from various European studies[50].

Figure 19 shows an overview of response-exposure curves from different European studies published between 2001 and 2015[50]. Although individual studies varied in size, the underlying research methodologies were similar or at least comparable. The figure shows the variance between airports, but also studies that focussed on the same airport, but with data collected in different years. For example, the data for Frankfurt airport suggests that the sensitivity to aircraft noise shifted by 20% for the same L_{den} between 2005 and 2013. While 61% of the respondents felt highly annoyed by a L_{den} of 65dB in 2005, this number increased to >80% in the 2015 survey. In itself, this is a remarkable finding, but it also suggests that factors other than the (equivalent) sound level are at play in relation to(aircraft) noise annoyance. Consequently, the variety between exposure-response curves has led to research that focused specifically on the relationship between noise exposure and annoyance, and then in particular the predictive power of metrics like L_{Aeq} and L_{den}.

2.5. Aircraft noise annoyance

The relationship between aircraft noise and annoyance has been studied since the late 1980s. In the 1980s, a study by Job[52] showed that noise exposure alone explained less than 20% of the variance in the responses to aircraft noise between participants[52]. Since the publication of Job's article, various other studies have presented comparable figures, with the percentage of variance in annoyance response attributed to acoustic factors varying between 33% and 12%[53,54]. Instead, the existing literature suggest that non-acoustic and personal factors account for the remaining variance. Literature therefore call aircraft noise annoyance a ‘socio-technical’ issue which cannot be explained and solved by changing the sound exposure level alone[54–56]. In the next sections, acoustic and non-acoustic factors that constitute aircraft noise annoyance are introduced in more detail.

2.5.1. Acoustic metrics

The most common and ubiquitous metric for traffic and aircraft noise is the equivalent sound pressure level (L_{eq}), with an A- or C-weighting[57]. The European L_{den} is a variation on the L_{eq} which awards penalty scores for certain sources or sound events for specific timeslots (evening and night). Alternatively, aircraft noise exposure is expressed by the EPNdB, SEL, peak levels (L_{max}) and the number of events[58]. The EPNdB is explicitly designed for aircraft noise and commonly used to compare flyovers and aircraft types. The EPNdB adjusts the sound signal for the duration of the sound event, but also includes a correction for tonal components coinciding with the human sensitivity to loudness[59]. The idea is that humans are more annoyed by tones in the frequency domain between 2000 and 4000Hz, and the sound energy is amended for these frequencies[59]. Although the EPNdB is used in both industry and academia, the metric is not popular in policy making and legislation. The SEL is calculated by integrating the sound energy divided across a time interval of reference, which is often one second[1,p. 153]. Generally, the *SEL* is used to compare individual sound events. The maximum sound level during an aircraft flyover is expressed as the L_{Amax}.

2.5.1.1. Exposure and response

Research focusing on the effects of acoustic measures on aircraft noise annoyance can be divided into two groups. The first group focuses on the relationship between annoyance and long-term exposure, based on periodical (postal) surveys. Often, the ordered category scale is used, in combination with absolute judgements[8,60]. Two opposite descriptors are placed on both ends, e.g. ‘very annoyed’ versus ‘not annoyed at all’, with successive or gradual intervals in between[61]. Researchers ask people to indicate their level of annoyance on the scale. If the study puts the focus on the long-term annoyance, people will be asked to rate the overall annoyance they experience. However, sometimes scientists are interested in to what extent annoyance varies over time or between individual sound events. In such cases, people are asked to rate their level of annoyance during time intervals[8]. The second group focuses on noise annoyance as experienced during a shorter period, e.g. a day or a week, with data acquired at a higher frequency, e.g. every hour. Acoustic metrics like the L_{Aeq}, L_{den}, L_{Amax} and/or the number of aircraft flyovers are often used in studies that focus on the relationship between annoyance and long-term noise exposure (see [43,50,62,63]). On the other hand, (acoustic) metrics like the location-adjusted sound level, (A)SEL, L_{Amax} and the time of the day are more common in studies with a focus on noise annoyance and short-term exposure (see e.g. [54,64–66]). The two groups are complementary, but the results serve different ends. While large scale surveys are used for noise policies, such as WHO guidelines[67], short-term exposure studies have a more explanatory and academic purpose.

Literature on long-term exposure shows that the L_{den}, L_{Amax} and the number of flyovers predict a comparable share of the variance in annoyance ratings between individuals[51,68]. Also, the L_{den} has an indirect impact on the level of annoyance, due to a small but significant effect on the perceived level of disturbance[68]. Disturbance only triggers annoyance when people feel they cannot control mitigating the noise and/or lack the ability to cope with it[68–70]. Literature on short-term exposure shows that the hourly number of aircraft flyovers with a peak level above 65dB(A) (NAT_{65}) is the best overall predictor for annoyance. However, when the sound level is adjusted for the location, i.e. whether a person was inside or outside a building, the adjusted L_{Aeq} is a better predictor for annoyance than the NAT. During the early mornings (7am-8am) and the late evenings (9pm-10pm), the tolerance for aircraft noise is lower, and a NAT >55dB(A) is more appropriate to predict annoyance. When people are performing a task, aircraft noise becomes annoying at higher sound levels compared to when people are not occupied and distracted. Additionally, when the sound level is increased incrementally, the level of annoyance rises more rapidly when people have to focus on a task[64]. For flyovers during night time, the number of flyovers is the most important factor for annoyance, followed by the equivalent sound level[66]. Sleep deprivation caused by aircraft noise might reinforce a negative feedback loop, with a build-up of less sleep leading to more annoyance (see e.g. [54,71,72]).

2.5.2. Non-acoustic factors

Non-acoustic factors are social, personal or context-related variables with a significant influence on noise annoyance[68]. Inherently, this means that the variety of research methods is wide. Literature suggests that non-acoustic factors account for most of the variance between individuals in aircraft noise annoyance ratings. An example of the role of beliefs is research on the influence of social-political framing and the perception of fairness. Broër[73], later in collaboration with Kroesen[74], showed that people's assessment of aircraft noise annoyance is influenced by the framing of noise annoyance in a wider social-political discourse. The individual perspective on aircraft noise annoyance gains a meaning once the issue is addressed, described and framed. Consequently, the same words and frames are adopted in society, spurring politicians and policy makers to address the issue, consolidating the urgency of the problem. However, the attitude and manifestation of aircraft noise annoyance both also depend on the belief in fairness. In this context, Maris[75] showed that fairness is the belief that a decision is made fairly, which is based on a sense of trust that the authorities have considered and weighed up all the different interests at stake to the best of their ability. Hence, when distrust towards authorities or airports increases, so does the level of annoyance experienced from air traffic. Other studies have showed that, on a personal level, noise sensitivity and fear have a large impact on the way people perceive sound[51,76]. Also, literature reports on a relationship between house ownership, annoyance and noise levels, and the socio-economic status of people[51]. Responders with a mid and high socio-economic background reported more annoyance than people in a low socio-economic group[51]. Studies presented opposing conclusions about the impact of demographic factors, meaning that there is no consensus about the influence of such factors on noise annoyance yet[76,77]. Stallen[70] suggested that coping plays an important role in the perception of noise annoyance. The conceptual framework is rooted in stress-theories and considers noise annoyance as a variation on physiological stress[68,70]. According to these theories, stress is the result of a balance between an individual's exposure to a threat and their resources to act on or deal with the threat[68]. Coping refers to the individual's ability to adjust the local environment to exogenous factors and to deal with a situation. What is needed varies between individuals and depends on the time, place and activity. Several studies also showed that a sudden increase or decrease in air traffic leads to an 'over-' or 'under-reaction' compared to the expectations[78,79]. This means that their level of annoyance rises faster, or drops further, than what would be expected based on dose-effect relationships.

Although there are plenty more studies on noise annoyance and non-acoustic factors to discuss, a fundamental shortcoming of the literature on non-acoustic factors and annoyance is that studies are mainly inductive[68]. This means that correlations are not based on a supporting theory, but on isolated statistical observations instead, which obscures the interpretation of the factors and causal claims[68]. Additionally, most studies are based on multiple regression analyses, but it is unclear whether this method is appropriate for situations with feedback loops between factors[68]. For Kroesen, Molin and van Wee[68], these two objections gave a reason to develop and test a theoretical model that could explain aircraft noise annoyance, based on the previous studies.

2.5.3. Causality and annoyance

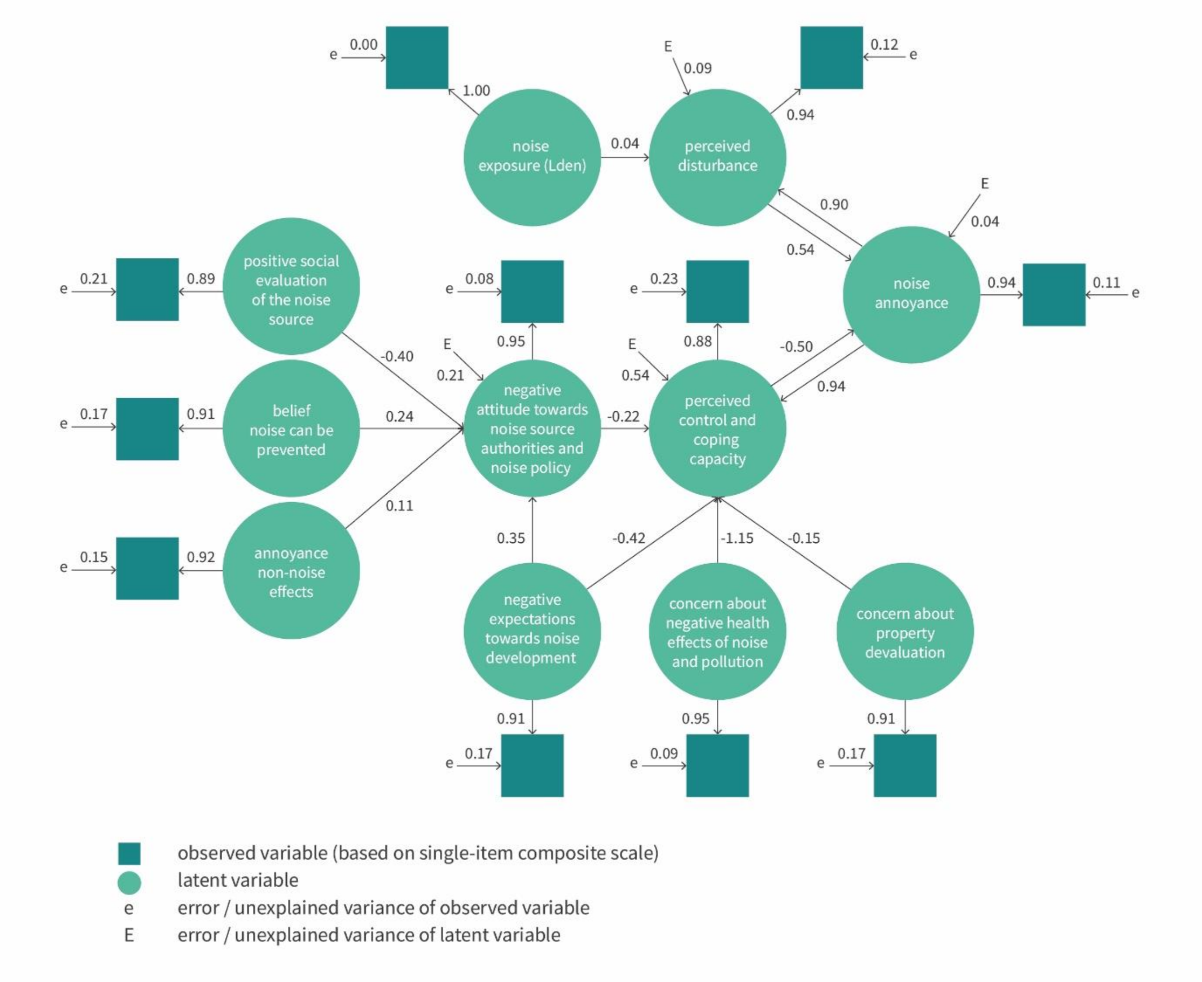

Figure 20 Structural equation model for aircraft noise annoyance, adapted from the work by Kroesen, Molin and van Wee[68].

Kroesen, Molin and van Wee used the framework by Stallen[70] as the supporting theoretical basis for their research. The model considered direct and reciprocal interactions between acoustic and non-acoustic factors. Variables were selected on the basis of meta-studies[42,52,53,77,80], and were only included if there was enough evidence for a factor's significance. Figure 20 shows the model and the quantified interaction effects, expressed by the standardized path estimates and the correlation coefficients. The model makes a distinction between disturbance and control as the two main contributors to aircraft noise annoyance. The final model was the result of two iterations. First, the factors and theoretical dependencies were combined with the framework by Stallen. Data from a survey was fed into the model, and only significant and independent factors were used for a second iteration. Figure 20 shows the effect sizes of factors and reciprocities between factors. For example, the figure shows that perceived disturbance (0.54) and perceived control and coping capacity (-0.50) are quite similar, and influence each other in, an almost, even and reciprocal manner[68,81]. Although the L_{den} is the only significant determinant factor for the perceived level of annoyance, the effect size is very small (0.04). Kroesen, Molin and van Wee[68] concluded that the concern about negative health effects of noise and pollution, perceived disturbance, perceived control and coping capacity and negative expectations towards noise development were the most important determinant factors for predicting aircraft noise annoyance. Kroesen and Schreckenberg[82] showed that a general attitude towards aircraft noise (GNR) forms a 'latent superordinate construct' that influences perceived noise annoyance, disturbance of activities, fear and health (both mental and physical)[82]. There is a strong correlation between the GNR and a negative response towards aircraft noise, and a significant but weaker correlation between the GNR, fear and health-related concerns[82].

2.6. Human cognition and sound

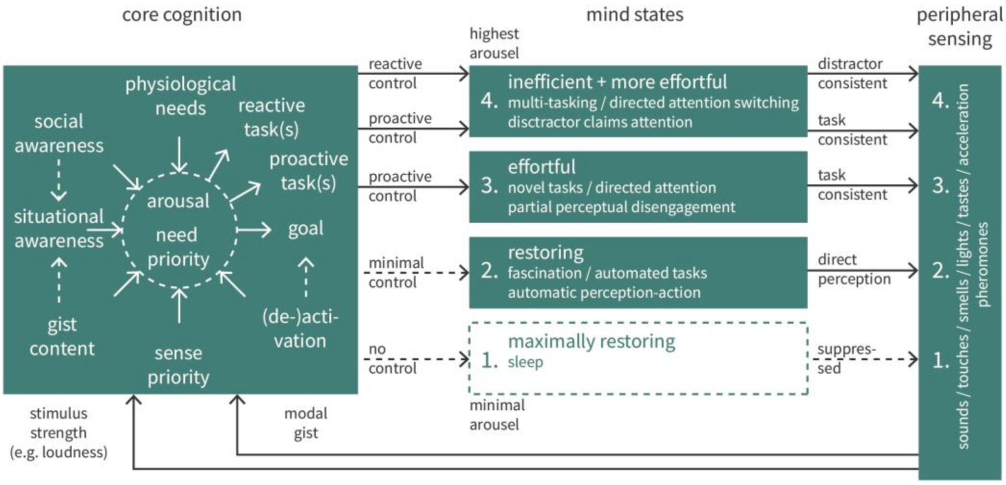

Figure 21 Descriptive model for the interaction between sensory stimuli, mind-states and the context surrounding an individual[83].

Stallen[70] and Kroesen[81]'s conclusions are backed up by other studies that put the focus on the human response to sound. For example, Andringa and Lanser[83] argue that (the perception of) quietness is linked to control over the 'state of mind', and to what extent exogenous factors impede this control. Like coping, control means that it is not the sound level per se that determines the level of annoyance, but rather how sound infringes on the individual's freedom to decide what to be exposed to. By combing through cognitive and evolutionary biology theories, Andringa and Lanser[83] developed an explanatory framework to explain the human interaction with their (acoustic) environment (see Figure 21). The framework describes the interactions between the surroundings (peripheral sensing), the cognitive evaluation (core cognition) of the environment, and the response (mind-state). The model was built on the premise that humans, like other species, constantly evaluate their surroundings for safety. This evaluation is important for their survival, and often occurs unconsciously within split seconds (modal gist) and while the environment is monitored simultaneously by multiple senses. Unless the information gathered matches expectations, the body is alarmed and starts to respond. Very loud sounds, blinding lights, strong stenches, stark temperature variations are all examples of sudden distractors that can change a person's physical state from relaxed to alerted. According to Andringa and Lanser, suspicious cues will make us more aroused and vigilant, and leave us with less mental capacity to focus on other (more sophisticated) tasks. Consequently, these distractors hinder humans executing a task and will make them feel distracted and limited in their states of mind. However, the sound source plays and important role as well. As the auditory environment around people is comprised of multiple sounds from different origins, arousal and distraction also depend on the constellation and saliency of various sound sources. Halpner, Blake and Hildenbrand[84] suggest that the human response to sounds varies, and relates to the way we are conditioned to identify warning sounds as indicating danger. This might increase the production of stress hormones which cause long term adverse health effects (e.g. cardiovascular diseases)[85,86].

2.6.1. Place, sound and perception

The models by Stallen[70], Kroesen[68], Andringa *and* Lanser[83] and Evans[87] show that, to a large extent, the experience of sound depends on the congruence between the environment and personal needs[70,83,88]. These needs are not fixed, and depend on activity, time of the day, mood and place. Sound is perceived as more annoying when it disturbs communication, relaxation or sleep[54]. Moreover, literature shows that, for the same L_{den} level, aircraft noise annoyance is worse when people are inside a building compared to being outdoors[87,89,90]. Andringa and Lanser relate this to the difference between public and private spaces, with the home as the ultimate example of private space. Or, as Evans, Wells and Moch put it, *"Home is a place that reflects identity and provides security and maximum control. Good housing offers protection not only from the elements but also from negative social conditions…. Poor housing quality reduces behavioural options, diminishes mastery, and contributes to a general sense of helplessness"*[87]. Sound annoyance is worse when people are dissatisfied with their neighbourhood, their house or the quality of the acoustic insulation in their house[51,54,91]. This is especially the case when the insulation is a form of compensation for (aircraft) noise and paid for by an (airport) authority[54]. Hence, good urban and architectural design can contribute to the reduction of noise annoyance, in direct and indirect ways. It can help directly by attenuating the sound levels inside and outside buildings. Indirectly, it can diversify the auditory landscape, by masking unwanted sounds and/or improving the overall satisfaction of residents. The next chapter will focus on the relationship between the built environment, design, noise abatement and auditory perception.

2.7. Summary

- Locally, buildings and surface materials can reduce the exposure to traffic noise, e.g. by increasing the friction induced by edges (diffraction) or the acoustic absorption of surfaces.
- An inhomogeneous atmosphere scatters and diffracts incident sound waves, which influences the propagation of sound if a source is positioned in the boundary layer, for example airplanes or wind turbines.
- Aircraft noise is a form of traffic noise, although that the position (height) of the source is radically different from other traffic sources.
- Aircraft noise can be broken down into eight categories, of which take-offs, landings, flying and engine-run ups are the noisiest. The directivity of the sound depends on the working mode and varies between (nearly) spherical (flying) to conical (take-offs / engine run-ups).
- As aircraft noise is scattered and refracted in the atmosphere, it is unclear to what extent buildings can be used to abate aircraft noise. This topic is studied and discussed in chapter 5.
- Noise contours and acoustic insulation schemes are the most prevalent noise mitigations around airports.
- Noise contours are based on the equivalent sound exposure level, assuming a dose-effect relationship. However, the dose-effect curves vary between individual studies and airports.
- Recent studies show that annoyance induced by aircraft noise depends on acoustic and non-acoustic factors. Acoustic factors explain about a third of the variance in noise annoyance ratings between individuals, the rest is attributed to non-acoustic (and personal) factors.
- Peak exposure levels ($L_{(A)max}$), average exposure levels (e.g. L_{den}) and the number of flight movements are examples of acoustic factors. Research suggests that the peak levels, the number of flight movements and the localized sound exposure levels are better predictors for the level of annoyance than the L_{den}.
- Non-acoustic factors, such as the perception of coping and control, are seen as just as important as the actual perception of disturbance (which is linked to the noise levels).
- Place, activity and the time of the day are also important predictors for the level of annoyance that people (may) experience. The more private the location, the more sensitive and disturbed people will respond to the exposure to exogenous sounds. Hence, measures to adjust the sound exposure levels around a receiver could help individuals to regain a feeling of control. This may reduce the level of annoyance people report and experience.

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3. Sound and the urban environment

In cities and towns, the perception and dispersion of sound is shaped by the design of urban areas. The previous chapter described how walls and surfaces reflect, scatter, absorb and transmit sound in indoor and outdoor spaces. However, the perception of sound does not only depend on the acoustic signal, but is also determined by factors like place, source, sound level, reverberation, the person's activity and the time of the day. This chapter presents a literature review on the impact of the built environment on the exposure and perception of sound. The chapter opens with an overview of literature focusing on the acoustic effects of buildings and urban designs. The second part of the chapter considers the role of architectural and urban design in relation to the auditory perception of places. Most of the available literature focuses on road traffic noise, bar a few exceptions.

3.1. Research on sound in urban areas

Within literature focusing on the acoustic behaviour of sound in urban areas, two types of research can be distinguished. The first type of studies focuses on the urban mesoscale and sound propagation, while the second type considers the urban microscale. Because of the difference in scale, the groups not only use different research methods, but also have different objectives. Mesoscale studies usually examine the relations between factors like street ramifications, population distribution, traffic flows, building heights and noise levels[1,2]. Instead of the sound levels for a specific position, studies focus on the statistical correlations, e.g. between the floor or ground space index and the overall sound exposure level in an area[3]. Most studies use heuristic simulation models, which are more practical for calculating the sound levels in cities than high-fidelity wave-based models. The latter offer a higher a level of precision and accuracy, but are significantly slower than heuristic models, and often limited to studying sound dispersion around three-dimensional geometries[1,3]. The next chapter will describe the differences and similarities between numerical acoustic models at greater length. In contrast to mesoscale studies, microscale studies focus on the impact of (a) building(s) on the sound dispersion within streets or towards adjacent courtyards. The impact of (an) architectural variant(s) is either benchmarked against a baseline scenario, like an archetype of a residential street, or expressed by the insertion loss. Due to the scale and size, most studies rely on numerical wave-based models, sometimes in combination with scale model and/or wind tunnel tests[1,4,5]. In general, studies on the propagation of sound in urban areas can be divided in three groups. The first group focuses on the impact of street and building geometry. Studies that belong to this group can be either meso- or microscale oriented, depending on the scope of an individual study. The second group is made up of studies on the acoustic effects of facades, roofs and ornaments. The third group comprises studies on (surface) materials and acoustic absorption.

3.1.1. Street and building dimensions

The first group can be broken down into different themes and scales. At one end of the spectrum, mesoscale studies focus on the more general effects of urban design and sound exposure. An example is a study by Salomons and Berghauser-Pont[2], exploring the relation between traffic noise and spatial form, which showed that a higher urban density results in lower sound levels. However, although tall and closed urban blocks reduce the sound level within the enclosed courtyards, the sound level within the streets between the urban blocks hardly change. In many mesoscale studies, the impact of sound is weighed up against the total number of people living in an area[1], which is important for urban planning and traffic management.

Acoustic mesoscale studies also considered the impact of street and building dimensions on the sound level within the source and adjacent canyons. A good example of this is Hoa and Kang's study on the influence of the urban mesoscale and aircraft. The study compared 25 urban areas, calculated the sound levels in the areas and then looked for correlations between sound levels and the 1) building plan area, 2) total area of rough surfaces, 3) total facade surface parallel to the flight path, 4) street width-to-building-height-ratio (W/H from now on) and 5) the horizontal distance between a flight path and the first row of houses. The results show the strongest correlation between the sound level in an urban area and the second and fifth factors. On the other hand, the first and fourth factors had no impact on the sound level. The study concluded that urban morphology has an important impact on the amount of aircraft noise in urban areas. For road traffic, urban mesoscale studies do not give a clear picture of the correlation between the W/H ratio and the sound level in a street. A study carried out in China found that rigid facades and smaller streets increase the sound level[6]. However, for cases in Spain and the Netherlands, studies have reported the opposite, that the sound level is higher in wider streets, probably because wider streets are busier with higher traffic speeds and volumes[2,7].

At the other end of the spectrum, microscale studies have focused on the W/H ratio as well, but have also looked at the noise situation for smaller areas with one or two canyons. For example, a computational study by van Renterghem, Salomons and Botteldooren[5] showed that W/H ratios less than 1 reduce the sound levels in receiver canyons. The study reported differences between the different ratios as over 20dB, especially for frequencies <400Hz and >1000Hz. However, for W/H ratios over 1, the sound level in the receiver canyon is more or less constant. For the sound level within source canyons, Hornikx and Forssén[8] found a subtle negative effect, i.e. the sound level increased as an effect of the street width. The sound attenuating effects of low W/H ratios are also highly dependent on the weather conditions[5].

3.1.2. Facades, roofs and ornaments

Facades ornaments, such as building protrusions including balconies, parapets and bay windows, diffuse the sound field in source canyons. Consequently, the sound levels in source and receiver canyons drop, as the sound energy that still leaves the source canyon is lower. Compared to a rigid facade, i.e. facades without ornaments or protrusions, balconies can cause up to 5dB in noise reduction, depending on the frequency (i.e. greatest reduction for frequencies >400Hz). Similarly, a tilted parapet (30°) bending towards the source can reduce sound for frequencies below 400Hz[5]. Except for higher frequencies, the tilted variant did not lead to more noise reduction than a straight parapet. Another benefit of tilted parapets and balconies is the extra shielding they provide near the facades within balconies[9]. This effect is most noticeable for the lower floors, which are closer to the sound source[9]. For aircraft noise specifically, facade protrusion can reduce reflections and diffuse the sound field near facades[10]. Scale model tests revealed a maximum sound reduction of about 4dB, based on a broadband source with a spectrum between 25Hz and 630Hz[10]. The design of roof tops also affects the sound level in adjacent canyons. A roof can increase diffraction by its shape, and thereby scatter the sound above the roof top[11]. For traffic sound moving between two canyons, a saw-toothed roof top abates the sound in adjacent canyons most effectively, i.e. reducing it by over 10dB(A). For specific parts of the facade, this level can exceed 15dB(A) for light vehicles[11].

3.1.2.1. Surface materials

When sound travels over a surface, the impedance of the ground can reduce the sound level that reaches the receiver by means of reflections and absorption. If the ground surface is reasonably flat, i.e. without hills or elevations, the surface absorbs incident sound waves, although the level of absorption depends on the frequency, angle of incidence and the surface material. Although an irregular terrain can also absorb incident sound, the scattering and abating effects caused by diffraction and reflections may outweigh the sound attenuating effects of the ground absorption. In general, porous materials absorb the incident sound better than rigid structures. This can be illustrated by a study that found that the sound level of a stationary aircraft engine 1000m from the source can be about 15dB quieter if the ground surface is formed by grass instead of concrete[12]. Porous materials such a thick layers of snow, forest mulch or gravel are likely to show even better results, as their flow resistivity is lower[13,14]. In cities, rough surfaces like walls or pavements scatter the sound waves and diffuse the sound field[5]. This also applies for absorbing materials mounted on walls in the street and adjacent canyons[8]. Consequently, less sound energy leaves the canyon, which results in lower sound levels in adjacent courtyards. Van Renterghem, Salomons and Botteldooren[5] estimated that the sound levels are about 10dB lower for irregular facades compared to rigid ones. Within streets, the structure and material of the facades play an important role in the transmission of sound. Kang showed that an extra sound attenuation of between 2dB and 4dB can be obtained when absorbent materials are mounted on the walls or ground surface[15]. Balconies with porous material glued on the ceilings or on the back of parapets reduce the sound levels on the balcony and near the facade[16,17]. The studies found a maximum additional attenuation of 8dB, depending on the floor level and dimensions of the balcony[17]. However, weather wearing effects and rain create a challenge for the applicability of porous structures in outdoor areas. An alternative are green walls growing on porous substrates. Green walls can yield a relatively high level of sound absorption, as long as the substrate is not too wet, with the foliage forming a protective layer covering the substrate[18]. Various studies showed the acoustic benefits of facade vegetation mounted on walls[19,20]. Green roofs can improve the noise reduction by about 10dB compared to a rigid roof[21–23]. Moreover, the combination of a diffracting roof shape and vegetation yields a cumulative reduction of noise[22].

3.1.3. Landscape features

Large-scale landscape features, such as hills and mountains, reduce the probability that noise will spread over a large area beyond a valley or enclosure. On a smaller scale, landscape features such as trees, tree belts and verges also substantially influence the propagation of sound. Forest or tree belts reduce noise in three ways[12]. Firstly, dead leaves form a porous layer of mulch on the forest floor, increasing the absorption of waves reflected towards the ground. Secondly, if dense enough, the foliage acts as a damping layer and attenuates incident sound through viscous friction[12]. Thirdly, the tree barks and trunks scatter and reflect the sound waves on the transmission path between a source and receiver. Trees and/or dense vegetation belts must be sufficiently wide to reduce noise from road traffic (i.e. motorways)[12].

Trees in streets will also scatter, absorb and reflect the sound, but to a lesser extent. Various studies show that vegetation belts can reduce traffic noise up to 10dB(A)[12,24], although the noise attenuation is much lower in the case of downwind refraction[12,25]. Foliage and leaves mainly reduce frequencies above 200Hz, while ground absorption has a larger impact on frequencies lower than 200Hz[12,26]. When it comes to reducing the noise emitted during the first part of an aircraft take-off, research has showed that the ground impedance level can make a difference[13]. A study showed that ploughing the ground on a regular basis can reduce low frequency sound in an area about 2000m behind the runway. However, vegetation also give the perception that noise levels are lower, even when the actual noise levels are unchanged. The perception of sound in relation to natural features will be discussed in the next section.

3.1.4. Quiet building sides

For road traffic noise, the relative difference of the exposure levels around a building also influences the level of annoyance. Several studies show that having access to a quiet facade can reduce the level of noise annoyance. In literature, a quiet facade can refer to a building side with an equivalent sound level below 45dB(A)[27] or 42dB(A)[28].However, the term also applies to building sides at which the relative difference between exposed and non-exposed facades exceeds 10dB[29–32]. Other studies point to the importance of 'quietness' and / or 'tranquillity' for the quality of the surrounding (acoustic) environment[28,33]. This can be described in acoustic terms, i.e. $L_{Amax} < 55$dBA or $L_{Aeq} < 42$dB(A), or as the relative variances between sound events[28,34,35].

3.2. Urban areas and sound perception

The dual meaning of quiet building sides, as both absolute and relative, shows that sound exposure levels and people's response are not necessarily congruent. Since the 1960s, researchers from different fields have collaborated to develop interdisciplinary research methods to study the reciprocity between context and the perception of sound. Many see the Canadian naturalist and musician Raymond Schafer as the founder of this discipline. Schafer was one of the first people who described the immersive and multifaceted character of sound and environments. Like the visual environment or landscapes, the auditory environment is the cumulation of individual sounds and experiences, resulting in a soundscape. To unify the variety of research and interpretations of what the term soundscape means, ISO standardized the definition in 2014. According to ISO, a soundscape is an 'acoustic environment as perceived or experienced and/or understood by a person or people, in context'[36]. Still, the variety of studies that relate to soundscapes is immense, ranging from ecological[37,38] to architectural (or urban)[3] and historical studies[39]. Soundscape studies often combine quantitative and qualitative research methods, such as acoustic measurements and surveys.

Due to the scope of this research, this section will only consider soundscape literature connected to the built environment. More precisely, this literature study focuses on urban contexts that yield a positive effect on the perception of the acoustic environment. In this respect, various studies explore the impact of natural features, i.e. the audio-visual interplay between the sound of moving water and vegetation and the potential of water sounds to act as acoustic maskers[40–46].

3.2.1. Perception of acoustic environments

The perception of the acoustic environment can be assessed in various ways. As the field is relatively young, the academic community is still working towards the standardization of research metrics and methodologies. In relation to noise annoyance, the sensation that a tone or sound evokes is often measured by its 'loudness' and 'sharpness'[47–49]. Zwicker[50] added the 'fluctuation strength' as a third factor to measure the level of annoyance. The main criticism for using 'noise annoyance' as a measure to describe the acoustic environment is that the wording inherently classifies noise as unwanted[49]. Instead, the quality or perception of an acoustic environment can be studied by asking people to rate its 'pleasantness'. As a descriptor, soundscape pleasantness relates to the roughness, sharpness and tonality of a sound[51]. However, Lavandier and Defréville[52] also linked soundscape pleasantness to the sound level of a source, and the duration people are exposed to a sound. An alternative way to study acoustic environments is to measure the 'quietness'[49]. As discussed, in relation to building sides, 'quietness' can be formulated in absolute or relative terms. The perception of quietness in relation to acoustic environments is not defined in more depth, other than the criterion that the sound levels should be >10dB lower near a quiet building side compared to the exposed facade. The 'slope' of a soundscape is a metric which can be used to describe the perceived quietness of an area[53–55]. The slope considers the number of sound events and the fluctuation of the sound exposure levels in an area over time[49]. On top of these metrics, a place can also be described in terms of the perceived tranquility, which relates to the amount of audible natural sounds and the sound levels, or the 'restorativiness' of a soundscape[28].

Axelsson, Nilsson and Berglund[56] analysed which latent variables are relevant descriptors for the quality of a soundscape. They showed that the factors 'pleasantness' and 'eventfulness', combined with 'familiarity', explain most variance of the soundscape perception between individuals (50%, 18%, and 6% respectively). Based on the results, Axelsson, Nilsson and Berglund[56] designed an explanatory quadrant for the quality of soundscapes, formed by two extremes. The soundscape perception is measured on a quadrant scale with the opposites 'pleasant versus unpleasant' and 'eventful versus uneventful' on the two axes. Axelsson, Nilsson and Berglund[56] characterized eight soundscape variants, all positioned in the quadrants between eventful and pleasant (see Figure 22)[56].

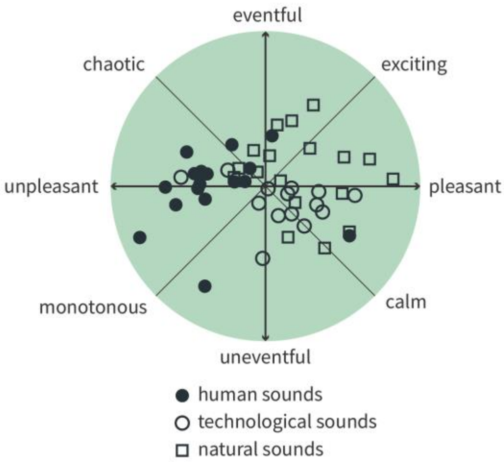

Figure 22 Octagonal projection of eight soundscape varieties with the position of human, technological and natural sounds, based on the results of a listening-test comprising 50 excerpts[56].

Because of the predictive power of the opposites 'soundscape pleasantness versus unpleasantness' and 'soundscape eventfulness versus uneventfulness' for the perception of soundscape quality, the model is frequently used to measure soundscape quality [57,58]. In general, soundscape pleasantness is associated with natural sounds while soundscape eventfulness represents the descriptions of liveliness and ambiance (e.g. the level of human sounds)(see e.g. [56,59]) (see Figure 22). Aside from the work by Axelsson, Nilsson and Berglund, various other studies focused on the perception of soundscape quality in relation to acoustic factors, such as the average sound pressure level and/or the temporal variability[53]. However, the results are not always conclusive, and some scientists have questioned the appropriateness to consider only acoustic measure in respect to the soundscape[53].

Finally, various studies stress the importance of the 'appropriateness' of an acoustic environment in relation to the visual surroundings[60–62]. In other words, an individual's expectations about the soundscape should be congruent with the actual soundscape of a place. This doesn't necessarily imply that appropriate soundscapes are 'good' or preferred[53]. Instead, appropriateness, or soundscape congruence, is seen as an additional criterion to rate the soundscape quality, together with variables such as the 'pleasantness' and 'eventfulness'.

3.2.2. Moving water and masking

Sounds from moving water vary in temporal variability, loudness and sharpness, and can be artificial or natural [44,63,64]. A few audio-only studies reported sea waves as the water variety that was rated most pleasant[44,65], but sea sounds are hard to implement in urban settings when designing for places that are not close to the coast. Water sounds do not improve the soundscape quality in all situations though[63], and therefore the right sound source must be carefully designed and selected before being implemented. For example, waterfalls or water features generating a relatively constant and low frequency sound were rated as less pleasant than babbling streams[44,63]. On the other hand, fountains with a lower sound level and high temporal variability were rated as most pleasant. The general effect of moving water on the perception of soundscapes is often linked to sound masking [66–68]. Sound masking techniques can be divided in two groups: 1) energetic and 2) non-energetic or informational masking. Energetic masking makes a target sound inaudible by adding sound with a similar spectral and power domain. In the second form of masking, the masking sound is (partially) different from the target sound, but creates uncertainty as to the target sound's origin and meaning. Therefore, it becomes harder to distinguish the target and masker sounds, thus increasing the audibility threshold of the individual sounds [67]. In urban contexts, masking is linked to the source prominence and hierarchy between fore- and background sounds, which make the soundscape of an area [58,59,69]. Literature showed that adding moving water changed what people saw as the most prominent source in a soundscape, which was seen as a form of non-energetic masking by the authors [59]. Water can energetically mask traffic noise, but only when the sound spectrum and temporal variance of the two (or more) sources coincide [40,64,70,71]. Galbrun and Ali[40] concluded that the frequency spectral components of road traffic make even the most preferred water varieties unsuitable for masking traffic noise energetically. However, studies suggest that added water features/sounds? can increase the auditory appraisal of road traffic noise by informational masking or distraction [40,43,64,72]. The sound level and spectral composition of added water features do not have to be equal to the traffic noise, but can enhance the soundscape quality when the water sound level is up to 3 dB(A) lower than the noise level of the traffic noise [40,42,72]. Carefully designed water features in public places could therefore improve the soundscape quality of urban environments that are contaminated with mechanical sounds.

3.2.3. Visible vegetation and sound perception

Studies on the effects of vegetation on sound appraisal range from research on the impact of landscapes and surroundings, to the role of trees and vegetation on walls, fences and (noise) barriers [73–77]. Traditionally, this was measured using projections and images combined with headphones or speakers, whereas now integral technologies like virtual reality (VR) have become more common [78,79]. Results from previous studies stress the importance of congruence between expectations and soundscape[73,74,76] and the positive effects of vegetation and natural visual cues in urban areas [76]. Additionally, it was found that the perception of noisiness decreases when a source remains partly visible through the greenery [77]. More recently, studies have explored the impact of green walls and trees in outdoor urban settings[42,78] through immersing participants in urban scenes by using projections or (more recently) virtual reality [78,80]. One finding was that vegetation, mainly in the form of trees, improved sound appraisal in an urban setting and scored more highly than other forms of vegetation like wall greening or shrubs [42]. Similar effects were found in a Belgian study where scenarios containing vegetation mounted on a fence over a motorway were the most effective in improving the quality of the soundscape [41]. On a larger urban scale, vegetation and access to green areas (e.g. parks or nature) contribute to a lower annoyance rating from traffic noise [27,81,82]. This is partly attributed to the restorative character of green areas, and partly to the aesthetic qualities of vegetation [45,81,83].

3.3. Summary

- Literature on the propagation of sound in urban areas can be divided in three groups, 1) city planning, 2) design of buildings and streets and 3) surface materials. The groups are based on the urban scale (micro versus meso) and a paper's research objectives.
- The acoustic effects of buildings and cities are usually studied by means of heuristic or wave-based acoustic computational models, which are discussed in chapter 4 in more depth.
- The dispersion of (road) traffic noise in between and around buildings depends on the architectural design, such as the shape of balconies, rooftops, the building height and street dimensions.
- Landscape features, such as hills or elevations, and acoustic absorbing surfaces, such as porous substrates or ploughed land, can reduce the intensity of reflected sound (ground) waves.
- Literature shows that the intensity of aircraft noise around buildings depend on the urban configuration of an area. However, it is unclear which design variables, like e,g, the geometry and materialization of buildings and streets, induce these differences around and between buildings. This question is studied in chapter 7.
- For road traffic noise, access to a quiet building side can reduce the perception of annoyance. A quiet building side can refer to a facade with a sound exposure level <45dB(A), or when

the relative difference between an exposed and shielded facade exceeds 10dB. In respect to aircraft noise, this theme is studied in chapter 5.

- Beyond the quantifiable acoustical description of a place, the acoustic environment or soundscape, can be characterized focusingin qualitative terms, e.g. based on the (emotional) perception of a place in respects to the sound(s).
- Soundscapes can be described in various ways and by means of a multitude of metrics. However, research showed that the best descriptors for the soundscape quality are the ‘pleasantness’, ‘eventfulness’ and ‘familiarity’, and the congruence between expectations about the soundscape and the visual environment. Hence, the constellation of sounds that blend together forming a soundscape can be influenced by adding, or masking, individual sources. Instead, also visual stimuli can be added or removed to influence the perception of the context and soundscape.
- Literature indicate that the presence of natural features, such as trees and moving water, improve the soundscape quality in areas exposed to aircraft noise. It is unclear to what extent natural features also influence the perception of aircraft noise, which is studied and discussed in chapter 8.

3.4. Literature

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4. Predicting aircraft noise around buildings

Numerical noise models play an essential role both in maintaining noise regulations and in acoustic research. Since computers have become faster, the available numerical methods have become more advanced, which has resulted in better and more accurate and viable models[1]. Today, numerical models are used for a variety of applications at different spatial scales. For example, numerical models forecast the equivalent noise levels around airports, or in cities, used to monitor excess sound exposure levels[2]. Auralization models are used in research and communication to render an immersive and realistic experience of a passing car or a flying aircraft [3,4]. However, each model has its limitations, and whether a numerical method is fit for purpose depends on constraints like time, spatial scale and noise source. While aircraft prediction models predict the sound pressure level for large areas, obstacles like buildings are omitted. Aircraft auralization models can adjust the sound signal to local weather conditions, but only consider ground reflections. On the other hand, urban acoustic models are used to predict the sound propagation around buildings or in streets, but often for a non-refracting atmosphere. Consequently, there remains a gap between the models appropriate to predict the propagation of aircraft noise and those models developed to predict the propagation of sound around buildings.

This chapter introduces the existing numerical models used both in academia and in real world applications to predict noise in cities and from flight procedures. Thereby, the chapter discusses the advantages, applications and limitations of the different models. The chapter commences with urban acoustic models, followed by aircraft noise mapping and auralization models. The second part of the chapter introduces existing ways to simulate atmospheric effects in the acoustic simulation models. Finally, the chapter presents an overview of validation methods and literature on the fidelity of acoustic simulation models.

4.1. Urban acoustic models

Urban acoustic models are used to study and map the propagation of sound in cities and around buildings. Whether a model is fit-for-purpose or not will depend on the urban scale and the objectives of an experiment or project. In literature, urban acoustic models are usually divided in two groups: 1) wave-based or physics models and 2) heuristic or engineering models[1]. Some scientists add a third group in addition to these two groups[5]. To avoid any possible ambiguity, only the terms ‘wave-based’ and ‘heuristic’ will be used in relation to both groups from now on. This third category comprises numerical methods which are either regarded as hybrids between the first and second group, or as methods which do not fit the traditional characteristics of the models in either group[5]. To avoid any ambiguity, the first group of models will be referred to as ‘wave-based’, the second as ‘heuristic’ and the third as ‘hybrid’ from now on. These three groups and their representative models are discussed in the following sections.

4.1.1. Wave-based models

The first group comprises numerical methods which calculate the sound pressure level by solving wave equations, hence the name 'wave' or 'physics' based models[1,5]. Wave-based methods predict the sound dispersion with a high accuracy, and generally focus on air pressure fluctuations within a time or frequency domain. The basis of wave-based models are mathematical formulae that describe the transmission of waves. If meteorological effects are included, the linear Euler equations are solved thus[1]:

$$\frac{\partial u}{\partial t} = -(u_0 \cdot \nabla)u - (u \cdot \nabla)u_0 - \frac{1}{\rho_0}\nabla p, \tag{4.1}$$

$$\frac{\partial p}{\partial t} = -u_0 \cdot \nabla p - \rho_0 c^2 \nabla \cdot u, \tag{4.2}$$

In these equations, c refers to the adiabatic speed of sound, ρ_0 to the atmospheric density, u_0 to the wind speed, u the acoustic velocity and p to the pressure. Alternatively, the wave equation is solved for situations without weather effects[1]:

$$\Delta p - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}p = 0. \tag{4.3}$$

Instead, a time-independent variant of the wave equation is given by the Helmholtz equation, used for the frequency domain[1]:

$$\Delta p + k^2 p = 0. \tag{4.4}$$

The equations illustrate that, even within the wave-based category, there are differences between the models which depend on the chosen numerical method. In a recent article, Hornikx[1] made an overview of the most relevant and widely used wave-based models (see Table 1). Without describing the advantages of each model, the table shows the range and differences between the existing wave-based methods. Again, the calculation speed and accuracy vary between the models, and depends on the context in which they are used. For example, PE models are relatively fast because they only consider the reflections in one direction, while reflections between walls are omitted. Another difference are the spatial limitations of the methods. While some models only calculate the sound transmission in a two-dimensional plane (e.g. the FDTD method)[6], others calculate the sound dispersion in all three directions (e.g. the PSTD method[7]). Due to the computational overhead, wave-based models are usually only used in academic studies. More specifically, wave-based models are often applied for urban microscale studies in which the propagation of sound in a street, or between a few canyons, is analysed. Within street canyons, meteorological factors such as the wind and temperature only have a small effect on the propagation of sound. Hence, many urban microscale studies omit atmospheric refraction. However, this does not mean that wave-based models are less appropriate for the simulation of atmospheric effects. For example, wind effects influence the sound propagation over roof tops or fields, and solutions have been developed for such problems[8,9]. At the time of writing, an interdisciplinary research project aims to combine CFD (computational fluid dynamics) and wave-base acoustic models[10]. The project seeks ways to improve the prediction of sound levels from distant sources in urban areas under different wind and weather conditions. Although first results have already been published, the final conclusions are expected around 2020.

Table 1 Comparison of various wave-based urban acoustic models by Hornikx[1]. TD refers to time domain, FD refers to frequency domain, and the signs +/-/o refer to the level of appropriateness of the model, + refers to high, - to low and o to medium. See[1] for the original source of the table.

Method	Type	Meteo			Reflection		Diffraction	Frequency	
		Mean profiles	Turbulence	Air Abs.	Geometry	Materials		Storage	Acceleration
PSTD	TD	+	+	+	o	-	+	+	+
FDTD	TD	+	+	o	o	+	+	o	+
BEM	FD	-	-	o	+	o	+	o	o
FM, BEM	FD	-	-	o	+	o	+	+	o
ESM	FD	-	-	+	o	o	+	o	o
TLM	TD	+	+	+	o	+	+	o	+
PE	FD	+	+	0	-	0	0	0	0
Modal/FEM	FD	0	0	0	-	0	+	0	0

4.1.2. Heuristic models

The second group comprises models with a lower fidelity than wave-based methods, but with a greater flexibility and faster calculation speed to predict noise in streets, neighbourhoods and cities. In contrast to wave-based methods, heuristic models compute the sound transmission between sources and receivers based on empirical observations and standarizations[11]. Hence, sound is not calculated as the air pressure within a time or frequency domain, but as the energy exchange between a source and a receiver[1,5,11]. Therefore, in the first instance, it is required to detect the possible propagation paths from a source to a receiver. There are different methods available to do this, and the appropriateness of each method depends on the application[11]. The image source method considers the boundaries of a (street) canyon as reflective, and mirrors the source positions by means of imaginary canyons[11,12]. Consequently, the sound level at the position of the receiver is the summation of the energy transmitted from the (centre points of the) image sources to the receiver as it would in a free field situation (no walls or grounds)[11]. To anticipate on the absorption of sound reflected against walls, the energy is corrected based on the absorption level of the rebounding surfaces. On the other hand, the ray-tracing method disperses a large number of densely-packed rays, traces the paths between the source and receiver, and determines the paths that cross the receiver[13,14]. Subsequently, only those paths that reach the receiver are selected for further analysis. The ray-tracing and image source methods are commonly used together in heuristic methods, although some models use alternatives such as beam or particle tracing[11]. Compared to wave-based methods, heuristic models are less accurate for large wave-lengths, multiple reflections and irregular surfaces[1]. For diffusely reflecting boundaries, the radiosity method is a viable alternative. The radiosity method divides a boundary into patches or nodes, after which the energy transmission between the individual nodes is calculated. The method is especially useful to predict the sound's reverberation time more precisely in a street canyon or square[11,15]. A higher reflection and diffraction order increases the accuracy of a method but also slows down the calculation speed[1]. The calculation speed and accuracy of heuristic models depend on the model settings to a much greater extent than wave-based methods, which simulate the spherical dispersion of a wave[1].

After the relevant paths, nodes or particles have been determined, the heuristic models calculate the overall sound levels as the summation of the energy that reaches the receiver. Again, this is radically different from wave-based methods, in which the sound level is calculated by integrating the pressure fluctuation on a time domain. In heuristic models, the energy transmission depends on the procedure or standards followed. Thus, heuristic models comprise two components: the path-tracing and the energy exchange algorithm. Examples of the latter are ISO 9613-2, Harmonoise and Nord2000[5,16]. ISO 9613-2 is a typical example of a heuristic method based on empirical standards. In ISO 9613-2, the total sound attenuation A is calculated as follows[5]:

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \tag{4.5}$$

In the equation, A_{div} refers to the sound attenuation due to atmospheric spread, A_{atm} to the atmospheric absorption, A_{gr} to the ground effect, A_{bar} to the attenuation from obstacles and A_{misc} to the sound attenuation from scattering zones such as dense vegetation. Alternatives, such as Harmonoise and Nord2000, follow a similar approach, i.e. the total sound attenuation is the result of individual contributors like atmospheric absorption, diffraction, ground reflections and so forth[16]. The main differences between different heuristic methods lie in the calculation procedures for these individual contributors. For example, Harmonoise and Nord2000 calculate the effects of edge diffraction, scattering zones, ground reflections and refraction differently[16]. Because heuristic models are regularly used to predict noise levels for larger urban areas with substantial distances between a source and receiver, atmospheric effects are rarely omitted. These are calculated differently though, depending on the model. The next section will discuss this in more depth.

Heuristic models are used for both micro- and mesoscale studies[11,12,15]. However, since wave-based models have become faster and more accessible, i.e. via open source codes, recent publications indicate a trend towards the use of wave-based models for urban microscale studies[1]. This is not the case for urban mesoscale studies and for real world applications, as heuristic models, which offer a good compromise between fidelity and calculation speed, are better suited to their requirements. Commercial acoustic calculation packages, such as Soundplan and Cadna, usually integrate various heuristic methods or standards into the model in combination with path-finder algorithms. For example, Cadna implements ISO 9613-2 for normal cases and industry noise, but integrates ECAC's doc 29 for aircraft noise, alongside two path detection algorithms. As calculation standards often vary between countries, this ensures that commercial packages can be exported internationally.

4.1.3. Hybrid models

Aside from these two groups (heuristic or wave-based models), there are examples of hybrid models that blend elements from both groups. For example, some methods combine a ray-tracing algorithm with solving the Helmholtz equation instead of empirical approaches to calculate the sound pressure level[17–19]. The advantage of blended approaches such as these is that it overcomes the problem heuristic models encounter, mainly for interference of low frequency sound[11]. Additionally, the ray-tracing part makes it easier to calculate the sound propagation over larger areas and for three dimensions, within a reasonable calculation speed. Statistical learning models are another example of a hybrid approach[5]. The models rely on (heuristic) data that is divided into binary decision trees, which are based on specified criteria. In the first place, these criteria are based on an underlying theory that describes the propagation of sound in outdoor areas. Subsequently, a neural network algorithm is trained to perform (regression) analyses. Like any neural network, the accuracy of the outcomes depends on the amount of data fed into the model.

4.2. Aircraft noise prediction models

Aircraft noise prediction and auralization models are structured in a similar way to heuristic urban acoustic models. Aircraft noise predication models such as FAA's INM, recently replaced by AEDT, and ECAC's doc.29, calculate the average sound pressure level in an area by using heuristic tabulated data[2,4,20]. To achieve a compromise between the calculation speed and the accuracy of such models, the distance between grid points is large (>10m)[21]. Consequently, relatively small objects, such as buildings, are omitted, and only ground reflections are considered[4,22]. The models compute the sound level in an area based on the power-noise-distance, normally at a height of 1.2m above the ground surface, and as a function of the thrust settings[4]. The NPD contains tabulated data of typical propagation profiles which are specified for aircraft and engine types, and/or for different flight settings and meteorological conditions. In order to take ground reflections and refraction into account, the models add a correction for the Lateral Attention (LA)[4,23]. However, as this is fairly simplified compared to reality, recent studies have tested more sophisticated methods of including atmospheric effects based on a ray-tracing algorithm[23]. Based on weather data, the ray-tracing component attributes a curvature to the propagation path between a source and a node representing an area. The outcome is then used as an overlay to correct the NPD data for atmospheric refraction. Due to the velocity of an aircraft, the angle the sound waves are dispersed at is constantly changing. Although the phase difference between direct and reflected waves can lead to interference, it is often neglected for noise mapping purposes. This is because the reinforcement and cancellation effects will alternate[4].

Like most heuristic urban acoustic methods, aircraft noise auralization models solve a ray-tracing algorithm to determine the sound propagation paths between a source position and a receiver[22]. Aircraft auralization models are used to create an immersive and realistic impression of an aircraft flyover for laymen. The position of the flight path and the receiver are usually fixed and preset[22], although there are also examples in which the receiver can move around[24]. In every case, the sound signal is adjusted for the binaural effects induced by head rotation. The propagation path must therefore be recalculated for each position, and is adjusted to the specific atmospheric conditions that apply to that path. If the distance between the aircraft and a receiver is great, atmospheric refraction can play a significant role to create a realistic auditory experience[4]. This means that the auralization models should anticipate on wind and temperature gradient, which can deform the sound signal[4,25]. However, research shows that atmospheric effects only render a signal clearly different, if the angle of incidence of the direct sound wave is <15°. Aside from refraction, the ground reflections will change for each position, and must be recalculated accordingly. To limit the computational overhead, auralization models only consider a very small number of ground reflections per path, and often only one[22,24]. The current generation of aircraft noise auralization models omit surface reflections and edge diffractions, although this will change in the foreseeable future[2]. A comparison between measurements of four aircraft flyovers and a synthesized aircraft flyover showed that interference effects were virtually absent in the measured data[26]; in fact, compared to the measurements, the numerical results overestimated the impact of interference. For this reason, the relevance of phase difference corrections to simulate interference between direct and reflected waves can be questioned.

4.3. Simulating atmospheric refraction

As discussed in the previous chapter, the scattering and refraction of sound waves is influenced by wind and temperature gradients in the atmosphere. This effect is most noticeable when walls or barriers do not surround a noise source (as they do in street canyons). For this reason, atmospheric effects are often omitted in urban microscale studies. However, for large distances between a source and a receiver (>100m)[14] or for sound propagating over features like roof tops, atmospheric refraction will come into play[1,9]. Refraction means that the speed of sound gradient changes, and thus the direction of the vector normal to the wave front. From a mathematical perspective, refraction is described by the laws of Snell and Huygen[14]. These laws state that at the border of two fluids with

[2] NLR recently started a research project on this topic.

different volumetric mass densities and with different speed of sound gradients c_1 and c_2, an incident plane wave will form secondary spherical waves. This will change the direction of the wave front, indicated by the angle γ. In Snell's law, this leads to the following equation[14]:

$$\frac{\cos\gamma_1}{c_1} = \frac{\cos\gamma_2}{c_2} \tag{4.6}$$

This means that the direction of the sound front (γ) changes as the speed of sound gradient changes in a different medium. Hence, if the speed of sound gradient of an air layer is known, the direction of the sound wave in the corresponding layer can be calculated.

In an ideal non-moving or homogenous atmosphere, sound moves with the adiabatic speed of sound. However, in an atmosphere with wind and temperature fluctuations, the sound rays movement is proportionally affected by the gradient of wind, sound speed and direction of the ray[4]. To reconstruct the path in such conditions requires complex differential equations. However, this is simplified by adding the wind velocity to the sound speed, which results in the effective sound speed c_{eff} ($\vec{n}$ denotes the ray direction, $\overrightarrow{u_0}$ the wind speed)[4,14,27,28].

$$c_{eff} = c + \vec{n} \cdot \overrightarrow{u_0} \tag{4.7}$$

Consequently, the direction of the wave front becomes subject only to the speed of sound. When applying this to rays, a ray's change of direction ($\vec{s}$) is proportional to the refractive index η ($1/c_{eff}$)[4].

$$|\nabla\tau| = \eta \tag{4.8}$$

This means that the normal of the wave front ($\nabla\tau$) only depends on the refraction index and is inversely proportional to the effective speed of sound[4].

$$\frac{d}{ds} = \vec{s} \cdot \nabla \qquad \Rightarrow \qquad \frac{d}{ds}(\nabla\tau) = \nabla(\vec{s} \cdot \nabla\tau) = \nabla\eta \tag{4.9}$$

A ray's change in direction with arc length $\vec{s}$ is defined by the gradient of the speed of sound in a layer[4]. For a simplified atmosphere formed by a fluid moving at the same speed and with the volumetric mass density, a linear speed of sound profile $c(z)$ can be formulated by the following equation:

$$c(z) = c(0)(1 + az) \tag{4.10}$$

In the equation, $c(0)$ refers to the sound velocity on the ground, c_0 to the speed of sound at the ground surface (340m/s under normal conditions) and z to the height. The factor a indicates the direction of the curvature $[(\frac{\Delta c}{\Delta z})/c_0]$, with positive values for downwind and negative values for upwind (using m/s) which depend on the wind speed[14,25]. However, as temperature and wind velocities change together with the height, the effective speed of sound also changes accordingly. This computes a logarithmic increase of the speed of sound profile, which results in a realistic profile of the effective speed of sound in the atmospheric surface boundary[14]. Salomons[14] described the relationship between the height z and the effective speed of sound as follows:

$$c_{eff}(z) = c_0 + a \ln\left(\frac{z}{z_0} + 1\right) \tag{4.11}$$

In the equation, the factor z_0 is the roughness constant, which depends on the ground surface.

In wave-based numerical methods, various solutions have been developed to deal with refraction and moving mediums. Examples of these are the PE (parabolic equation), FFP (fast field program) and CNPE (Crank-Nicolson parabolic equation) methods[1,14]. The methods yield accurate results but usually perform the calculations in a two-dimensional plane[14]. As a ray-tracing model is used in this research, the chapter will not discuss these methods in depth.

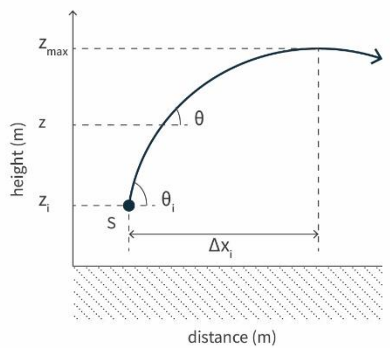

Figure 23 Linear speed of sound gradient and refraction of a ray, representing the propagation path of sound, between a source (S) and a receiver (R)[29].

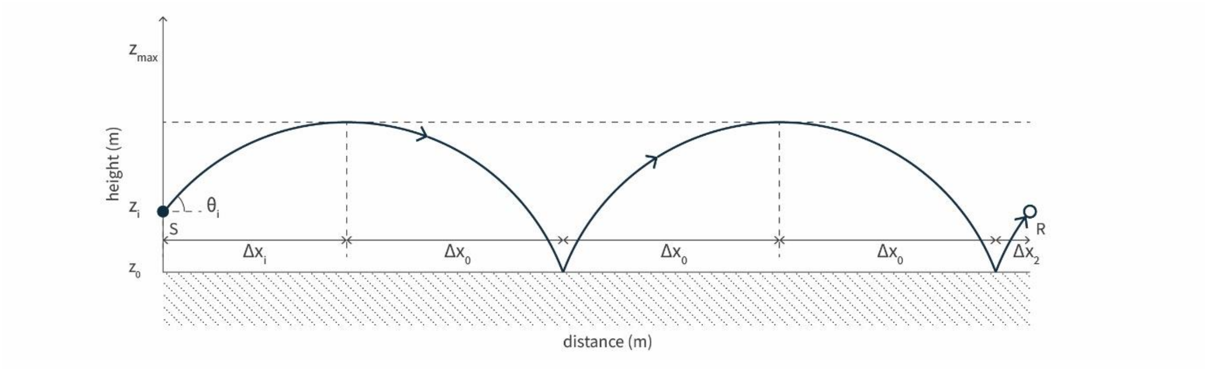

Figure 24 Linear speed of sound gradient and refracting rays for a strong downward refracting wave[29].

In ray-tracing-based acoustic numerical methods, refraction can be simulated by attributing a curvature to a path, based on a (series of) linear gradient(s)[14]. This means that a normally straight path is divided in smaller segments, and each segment corresponds to the speed of sound gradient of the layer in the relevant atmosphere. Consequently, the total curvature is the summation of the combined angles. However, a full and detailed reconstruction of the curvature requires complex prediction models. Instead, many heuristic acoustic models assume a linear speed of sound gradient for the atmosphere. This means that the rays bend like circular arcs. For moderate downward refraction, only the curvature of the direct path and the ground reflection are of interest (see Figure 23). In case of strong downwind refraction, or for large(r) distances between a source and a receiver, additional arced reflections on the ground surface come into play, and these can be determined by a fourth-order equation[29,30] (see Figure 24). Without going into great detail, the equations show that the speed of sound gradient determines the direction of the sound wave in a non-homogenous atmosphere. While a single gradient assumes a linear gradient for the whole atmosphere, more sophisticated methods divide the atmosphere into different layers, and determine the gradient using Snell's law.

4.3.1. Refraction in heuristic and auralization models

To calculate the effective speed of sound based on the meteorological conditions, different equations describe the relation between the wind speed, temperature and height. Attenborough[25] demonstrated the relationship between the speed of sound $c(z)$, wind speed $u(z)$ and temperature $\mathrm{t}(z)$ at height z as follows[25]:

$$c(z) = c(0)\sqrt{\frac{t(z) + 273.15}{273.15}} + u(z) \tag{4.12}$$

Heuristic urban acoustic models deal with refraction in various ways. Some methods, such as ISO 9613-2, do not specify further standards for the calculation of refraction[31]. However, numerical methods such as Nord2000 and Harmonoise include the option to adjust the sound pressure level for atmospheric effects. One of the main issues with refraction is achieving the right the balance between accuracy and numerical complexity. This issue also arises in the numerical approaches developed for refraction. Although a linear speed of sound gradient is a simpler approach to correct a ray for atmospheric effects, atmospheric refraction is seldom linear. Instead, the velocity increases almost logarithmically during the daytime, with a similar profile for the atmospheric speed of sound. To achieve a compromise between simplicity and accuracy, Nord2000 and Harmonoise compute a linear approximation of a logarithmic profile[16].

Both methods use a similar approximation for the vertical sound speed gradient $c(z)$, consisting of a logarithmic (A) and linear part (B) and explained by the following equations[32]:

$$c(z) = A ln\left(\frac{z}{z_0} + 1\right) + Bz + c(0) \tag{4.13}$$

$$A = \frac{u(z_u)}{ln\left(\frac{z_u}{z_0} + 1\right)} \tag{4.14}$$

$$B = \frac{dt}{dz}\frac{10.025}{\sqrt{t + 273.15}} \tag{4.15}$$

In A, u refers to the wind speed component in the propagation direction and z_0 is the roughness factor of the surface. B depends on temperature t, assuming a linear increase of temperature by height. Consequently, a linear approximation a is calculated for the whole path between source and receiver[32]. Although the basic equations for refraction in Harmonoise and Nord2000 are comparable, the models use the equations in a different way. While Nord2000 bends the rays according to the calculated curvature, Harmonoise curves the ground surface[16]. For calculating refraction, the Nord2000 model is viewed as more accurate than the Harmonoise method[5,16].

An alternative method was developed for the auralization of aircraft noise was one in which the propagation path is adjusted based on meteorological data. Instead of a linear approximation, the curvature of the propagation path is based on Snell's law[4] (see equations 7, 8 and 9). This means that the path is divided in segments, and the direction of the path depends on the wind velocity in the air layer relating to the segment. In theory, more sophisticated options are also possible. However, as the auralization model must recalculate the paths and curvature in split seconds, the process requires a relatively fast algorithm to solve this. Research showed that the results computed by refracting rays are not always different from straight rays. If the incident angle at the receiver's position is higher than 15 degrees, the numerical results of curved and straight propagation paths are similar or sometimes even identical[22]. However, this conclusion only applied for scenarios without walls or obstacles around a receiver.

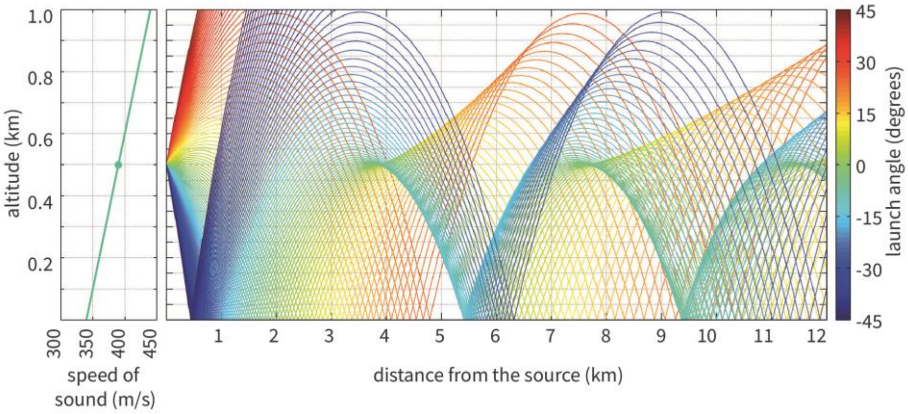

Figure 25 Rays dispersed by a source at an altitude of 500m propagated in an atmosphere with a downwind refracting linear speed of sound gradient of 0.1s^{-1} (adapted from[4]).

The solutions for refraction in ray-tracing methods also cause problems which are not an issue with wave-based models. The first issue is caustics, which are concentrations of rays, or places where the distance between the rays seems to vanish when rays cross paths[4,14]. Consequently, the algorithm predicts an infinite sound pressure at the position of the receiver, which is not realistic. Caustics are visible in Figure 25 around 5.4 and 9.2 km. To deal with caustics, different solutions have been developed for auralization and heuristic models (for examples see these studies[4,14]). The second problem is the so-called shadow zones, which are areas in which no rays can reach a receiver[14,29]. This only happens for upwind refraction, and a model based on ray-tracing will be unable to compute the sound level at positions within such areas. As for caustics, there are alternative solutions to correct the ray-tracing algorithm, and to estimate the sound level for positions in the areas. However, if no solution is implemented in a model, the algorithm will return an unrealistic result (zero) or lock itself in a loop. Although the sound pressure in such areas will be lower than for areas directly exposed to the sound waves, it will not be zero, due to atmospheric scattering and diffraction[4,14].

4.4. Predicting aircraft noise around buildings

The current generation of aircraft noise mapping and auralization models are unfit to study the behaviour of aircraft noise around buildings. There are a few examples of studies which have presented research on the current models' unsuitability or which have tested alternative numerical approaches. Donavon[33] published one of the first studies on this issue. In Donavon's scale model experiment, a low-flying aircraft was simulated by means of a small propeller moving above a street canyon built from wooden blocks. The impact of the buildings or blocks on the sound levels was small, and in the order of 1dB[33]. More recently, some studies have focused on the effects of low-flying military aircraft[34] and helicopters[35], and others have measured the sound exposure around buildings directly or almost directly underneath flight paths[36]. These studies reported similar effects to those found in Donavon's study.

Ismail and Oldham[12] were the first scientists who published a numerical method to simulate the propagation of aircraft noise in street canyons. In their study, a low flying airplane (60m altitude) was simulated as a spherically radiating point source, using a commercial engineering model (Raynoise) and a specular image source model, for diffuse and smooth surfaces respectively. In the experiment, a generic broadband source was used, while the model used a reciprocity approach. A reciprocity approach is a numerical procedure in which the position of a moving source is kept constant, while the position of a static receiver is gradually changed. As the distance between the source and the receiver was relatively small, atmospheric effects were neglected. The results were comparable to those presented in the previous measurement and scale model studies.

Hao and Kang[37] developed a similar approach but simulated an aircraft flyover as a cylindrically radiating line source, using a commercial simulation package (Cadna). Hao and Kang[37] varied the height and distance of the flight path in relation to the first row of buildings, and calculated the sound levels for different urban configurations. In total, the sound levels were calculated for 25 urban areas. The maximum altitude was 400ft (≈122m) and the maximum horizontal distance between the source and the first row of buildings was 1000m. The study focused on the sound levels between the buildings for three frequencies (630Hz, 1600Hz and 3150Hz). The results showed that urban form has a significant effect on the sound levels on street level. As in the study by Ismail and Oldham, Hoa and Kang assumed a non-refracting atmosphere, i.e. straight propagation paths.

4.5. Model validation and measurements

The suitability of an acoustic numerical model depends on the context and the objectives of a study or project. To establish the accuracy and limitations of a model, there are three ways to validate a numerical method. The first approach is to compare the data collected through measurements in scale model experiments, e.g. in wind tunnels or anechoic rooms, and with a numerical model generating the results[38,39]. The advantage of this approach is that all the variables in the experiment can be fully controlled. A second approach is to compare a numerical model with data collected through in-situ measurements[18,25]. This approach provides the most realistic impression of the sound fields in urban areas. However, a clear downside is the relative lack of control over the experiment and any unforeseen or non-linear variables that may influence the results. For example, wind factors, such as atmospheric turbulence and eddies, scatter and refract the sound, but are difficult to map and measure without additional equipment and CFD models[26]. The third approach is to compare the results from a model with those from other (already validated) models[5,40].

4.5.1. Urban acoustic models

Generally speaking, heuristic and wave-based models are validated in very similar ways[16,18,41]. To determine the deviation between measurements and numerical predictions, often the relative difference between a scenario with and without surfaces (free field) is calculated. In the context of acoustic numerical methods, a free field refers to a scenario in which only direct waves are considered, and reflections against (ground) surfaces are omitted. However, it is also common to calculate the excess noise attenuation with respect to a baseline scenario[42] or the reverberation time in street canyons[15]. When it comes to determining whether a model's fit or error level is acceptable, the existing literature does not indicate a standardized threshold or limit, although a mean deviation of <3dB seems widely accepted[1,16]. However, this limit is not set in stone, as in a study using a coupled wave-based PE and FDTD model, the maximum differences between measurements and calculations were ≈5dB for particular freqeuncies[38]. Still, the model is seen as accurate, because the results of the model and the measurements were comparable for most situations, and differences were usually substantially lower than 5dB[38]. The error between models and measurements increases for more complex urban forms though, or for greater distances between a source and a receiver. In a study on the propagation of sound over a wall in a wave-based PE model, incidental errors exceeded >15dB for particular scenarios[39]. This also applies for heuristic models such as Harmonoise and Nord2000. The results of numerical predictions and measurements are congruent as long as the scenario is relatively basic, such as the propagation of sound over a ground surface or a single (low) barrier[16]. The error rate increases for more complex forms, e.g. hills or slopes, with incidental errors up to 7dB[16]. However, in a validation study comprising many scenarios and comparing the Harmonoise and Nord2000 model with scale model tests, the mean error was <3dB and thus the models were deemed acceptable[16]. In general, literature shows that the Nord2000 and Harmonoise methods are more prevalent and accurate than ISO 9613-2, especially when the atmosphere is non-homogenous[5,16,43]. There were similar findings for numerical models benchmarked against in-situ measurements. For instance, in a scenario with sound propagating in an upwind turbulent and refracting atmosphere above a flat field, the maximum deviation between a wave-based FFP model and measurements was ≈4dB[25,44]. These results are similar for acoustic models that are not irrevocably wave-based or heuristic. For example, the results of measurements carried out in an ancient Greek theatre deviated with a maximum of ≈7dB compared to a hybrid numerical model[18]. However, for most scenarios the errors were smaller, and the mean results of the model agreed with the measurements.

4.5.2. Aircraft prediction models

The results of noise prediction models such as INM and doc.29 are based on noise profiles specified for combinations of different variables, such as the type of aircraft and engines during specific flight procedures and weather conditions. The data fed into the model is based on measurements, which means that further validation of the models is not required. However, the prediction models are usually influenced by political decisions made between airport and governments after consultation with local representatives. This means that the outcome of a noise prediction model represents the idealized situation in the first place. However, because the actual situation can be different from the idealized scenario, many airports are obliged to review the noise emissions annually[45,46]. If the weather in a particular year was different from the average weather statistics, or if more flights landed or took-off at night, the contours on the noise map will change. The actual noise maps can be based on measurements around an airport, but also on calculations. When noise maps are based on calculations, the same noise prediction model is used, but the data inserted into the model is updated and based on the actual flight movements. The results can be used to hold airports and airlines accountable, even though the results are not used to validate the model itself.

This is different for aircraft noise auralization models, as the models synthesize the sound signal, or adjust the signal based on the changing position of the receiver or the source. Hence, models are either compared to results from wind-tunnel tests or measured in-situ[4,24]. For example, a validation study by Arntzen and Simons[22] showed that the results of their auralization model were similar to measurements[26]. In the study, the model fit is expressed by the ΔSEL and ΔL_{Amax} values, i.e. the difference between measurements and simulations. Based on the comparison of four flights (all B747-400 with the same engine), the peak levels deviated by a maximum of ≈2dB(A). For SEL values, the maximum difference was ≈4dB(A). However, differences were substantially larger for specific positions on the time axis around the position of the L_{Amax}. The study showed differences of up to 10dB which were attributed to atmospheric turbulence and wind gusts scattering the sound waves along the propagation path[26].

4.6. Summary

- Urban acoustic simulation models can be divided in three categories: 1) heuristic (or engineering) models, 2) wave-based (or physics) models and 3) hybrid models.
- Wave-based models offer a higher level of detail and accuracy compared to heuristic models, but often lack the flexibility to simulate larger areas and compromise on calculation speed.
- In heuristic models, engineering methods, such as ray-tracing and image source algorithms, are commonly used to determine which propagation path(s) between a source and receiver are most relevant. To a lesser extent, this also applies for hybrid, aircraft noise mapping and (aircraft) auralization models.
- Heuristic urban acoustic models were used to predict the propagation of aircraft noise around buildings and street canyons in previous studies. However, these studies omitted weather effects, assuming a homogeneous and non-refracting atmosphere. As discussed in chapter 2, atmospheric effects gain importance for the prediction of sound if a sound source is positioned in the atmospheric boundary layer.
- In heuristic models, atmospheric refraction is simulated by adding a curvature to (a) propagation path(s). The curvature can be a composite of various directional vectors, based on the normal of the wave front per layer, or a single linear gradient. The latter significantly reduces the computational overhead of a model but is a less accurate method to simulate

atmospheric refraction. Literature shows that the first method is used in aircraft auralization models, which increases the accuracy of the calculations. The curvature is based on the relevant meteorological conditions per layer.

- (Heuristic) urban acoustic models often calculate a single gradient for a refracting atmosphere, based on e.g. a linear approximation of a logarithmic speed of sound gradient. This raises the question if an alternative method, based on aircraft auralization models, could improve the prediction of aircraft noise around buildings in a (heuristic) urban acoustic simulation model. This question is studied and discussed in chapter 6.
- Acoustic simulation models are validated in many ways. Based on the literature review it can be concluded that there are no formal guidelines or criteria on which basis models are rejected or accepted. However, literature suggest that a model is ‘acceptable’ if the average discrepancy between a model and a benchmark case is <5dB, while an average discrepancy <3dB is considered as an indication of a good model fit. However, even when the overall model fit is good, model discrepancies exceeding 10dB for specific frequencies or cases are not uncommon. This forms the backdrop for the study presented in chapter 6.

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part I *core research*

5. The quiet side of buildings exposed to aircraft noise: in situ-measurements on the noise reducing capacity of buildings during take-offs[3]

5.1. Abstract

The design of buildings and cities can reduce the sound level near facades, especially for facades which are not directly exposed to the sound source. The properties of quiet building sides have been studied in relation to road and rail traffic at length. However, research on noise reduction by buildings exposed to aircraft noise is limited, especially for buildings which are not directly under and further from flight paths. This study compared the noise levels near the exposed and shielded sides of buildings exposed to aircraft noise. The results of 168 take-offs at three locations were analysed, all at least 200m away from the mean ground track of the flight path. The mean noise reduction around buildings (ΔL_{Aeq}) varied between 13dB(A) and 2dB(A). The mean maximum exposure levels (L_{Amax}) were below 65dB(A) and significantly lower for the shielded facades in comparison to those exposed. Taller buildings showed a stronger noise reducing effect, while bays shorten the duration of exposure. The study found a significant non-linear correlation between the source position and noise reduction around buildings, even though the majority of the variance in ΔL_{Aeq} remained unexplained. The results indicate that the design of urban areas around airports can reduce excessive noise exposure.

5.2. Introduction

Aircraft noise causes stress-related complaints and has a negative impact on the well-being of residents living close to airports[1,2]. To protect people from excessive noise exposure, noise contours are a commonly used policy instrument, which restrict and regulate the expansion of urban areas where the noise levels exceed the legal thresholds[1]. Within the EU, contours are calculated on the basis of the European Noise Directive (END), which maintains that noise levels are based on the weighed equivalent sound levels (L_{den} and L_{night}) [3–5]. However, sound exposure does not automatically lead to annoyance, but rather is the consequence of reciprocal processes between exposure, context and response[6–9]. Since the 1960s, cross-disciplinary research has focused on the relationships between annoyance, noise levels and perception of (aircraft) noise (see e.g. [7,10–17]). As with other sound sources, literature shows that the level of annoyance evoked by aircraft noise largely depends on non-acoustic factors and context specific conditions (see e.g. [7,8,10–13,18]). For example, the average noise level (L_{Aeq}), often the bedrock metric in noise policies, predicts less than a third of the variance between individual's annoyance levels[7,11,16]. Factors like the duration of exposure, the location of the receiver, the maximum exposure level (L_{Amax}) and the number of flyovers correlate more strongly with

[3] This chapter is co-authored by Dr Maarten Hornikx (second author), Jian Kang (third author) and Koen Steemers (fourth author), see appendix B for more information.

the level of aircraft noise annoyance than the $L_{(A)eq}$[7]. The location (outside versus inside and the activities undertaken by respondents were found to be the best indicators for the level of short-term annoyance levels during an aircraft flyover[7]. With regards to the acoustic metrics, peak exposure levels (L_{Amax}) above 55dB(A), and especially above 65dB(A), are better predictors for the level of annoyance than the equivalent sound exposure levels.

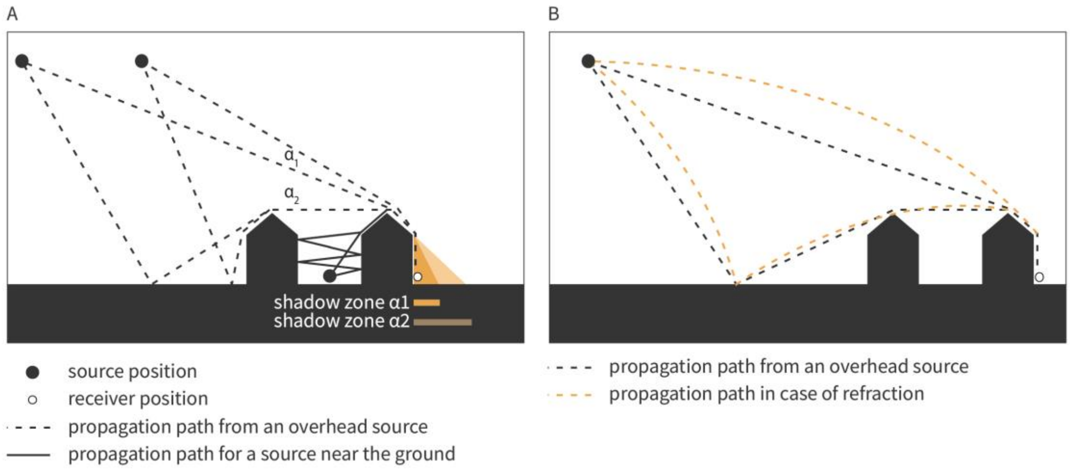

Figure 26 A) Two source positions with schematic sound paths: being reflected, diffracted around buildings. B) Schematized effect of refraction versus sound propagation without atmospheric refraction.

Literature on the annoyance-reducing effects of quiet building sides show the importance of context for the level of noise annoyance. For road traffic noise, a quiet building side is defined as a facade without a direct line of sight to the noise source (*n*LOS from now on), where the L_{Aeq} is <45dB(A), or where the relative difference with the exposed facade (L_{Aeq}) is >10dB(A)[19–24]. The shape and surface characteristics of buildings and streets can abate sound levels around or between buildings to meet the criteria for quiet facades (for example see e.g.[25,30,34]). Roof shape, (green) cladding, urban density and building dimensions scatter, diffract or absorb sound, as the sound energy decays due to reflections and diffraction over ridges and protrusions[25–33]. Since the noise reducing capacity of smart building designs are largely studied in relation to road and rail traffic, it is uncertain to what extent buildings can reduce aircraft noise as well. Theoretically, the position of aircraft means that sound is dispersed from above, limiting the sound abatement by building edges (see Figure 26) (see e.g.[35–37]). Furthermore, the direction from which the source emits noise, in combination with refraction, changes the angle of incidence of the sound waves as they hit a building[38–40]. This can negate or greatly reduce the noise abating potential of buildings and tall barriers (see Figure 26b)[38,39,41]. For buildings close to the ground track of a flight path, buildings and streets scarcely attenuate any aircraft noise, which means that the sound level near *d*LOS *(direct line of sight)* and *n*LOS facades are almost equivallent[42–44]. Moreover, reflections between buildings can amplify the sound level (i.e. L_{Amax} levels) within streets with buildings on both sides[42,44]. This is different for sites at the flanks of a flight path, where the horizontal distance between the ground track of an aircraft flyover and a building is larger. A computational study comparing twenty urban locations located less than 1000 metres from a flight path (altitude: 100-200ft) found differences up to 4.6dB between the individual locations[36]. This suggests that urban and architectural shape may reduce aircraft noise in such areas. But, because the study focused on the urban mesoscale, the variations in noise levels around individual buildings were not reported. The results are not backed by measurements or follow-up studies, and atmospheric effects were not considered. This raises the question as to what extent buildings can reduce aircraft noise when the horizontal distance between an aircraft and a building is substantially larger.

This chapter presents the results of an exploratory measurement study, in which the sound levels recorded near exposed and non-exposed building sides were compared. To the best of the author's knowledge, no similar study for urban areas at a substantial horizontal distance from flight paths has been published before. A substantial distance is commonly defined as a horizontal distance >200m between a building and the mean ground positions of a flight path and a vertical flight altitude >400ft (≈123m)[36]. This study had two objectives:

1. To examine if sound pressure levels vary around buildings exposed to aircraft noise, and to what extent this yields a 'quiet' building side.
2. To examine if the position of the sound source and the slant angle predict the difference in sound pressure levels around buildings exposed to aircraft noise.

The chapter will introduce the research methodology and case study locations first. The second part of the paper presents the results and compares them with the results for other sound sources. The paper closes with the conclusions.

5.3. Materials and methods

5.3.1. Site description

Acoustic data was recorded at three sites exposed to the noise from flights departing from Schiphol Amsterdam Airport's Kaagbaan runway (see Figure 27). Only data from take-offs was analysed, as aircraft produce more noise distributed over a wider spectrum during departures compared to landings[2,41]. Measurements were carried out during the summer of 2016, with one or more measurement days per site. Meteorological data such as the hourly temperature, wind speed and wind direction was assigned to the acoustic recordings (see 5.3.2.4). Microphones were placed in front of and behind a single building with two or three buildings per site (see Figure 27). To limit the influence of background noise, the sites were at a distance from busy roads and (noisy) public areas as far as was possible (i.e. business parks during the summer).

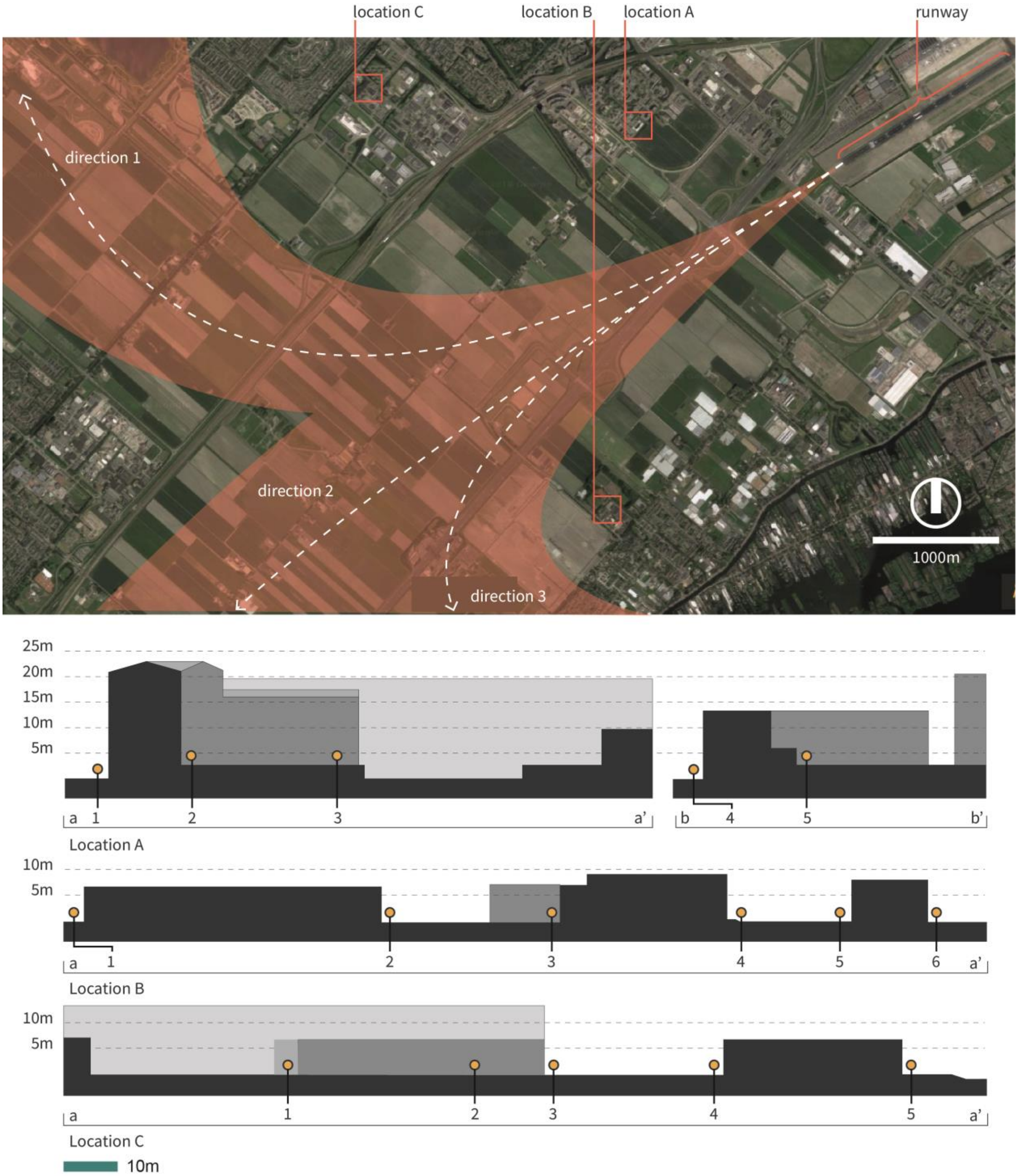

Figure 27 Locations A, B, C (photos and sections), flight paths 1, 2, 3, and positions of the microphones for each location (source images: Google Maps)

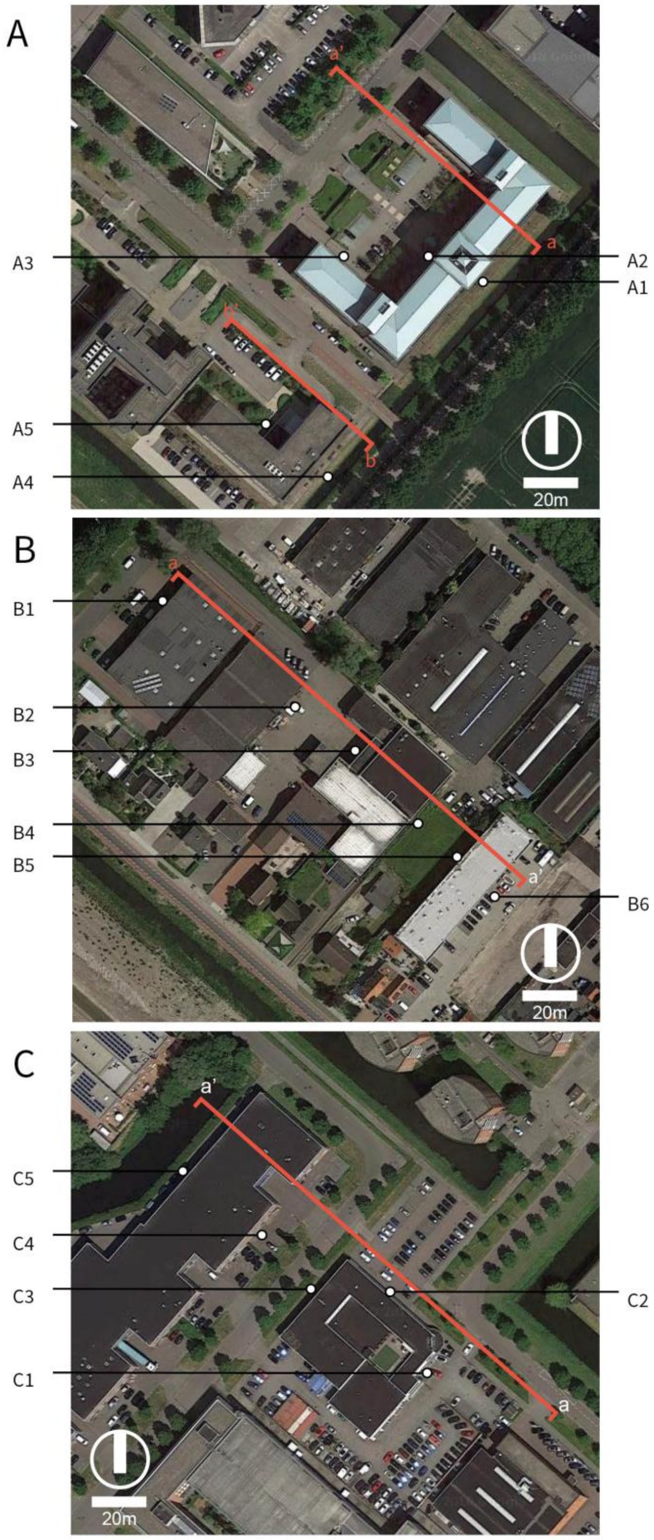

Figure 28 Aerial photographs of the case study locations, including the positions of the microphones (numbers) and the sections (a – a') as shown in Figure 27. The pairs of microphones per location are the microphone pairs: A1-A2, A1-A3, A4-A5; B1-B2, B3-B4, B5-B6, C1-C2, C4-C3, C4-C5

5.3.2. Acoustic instrumentation and processing

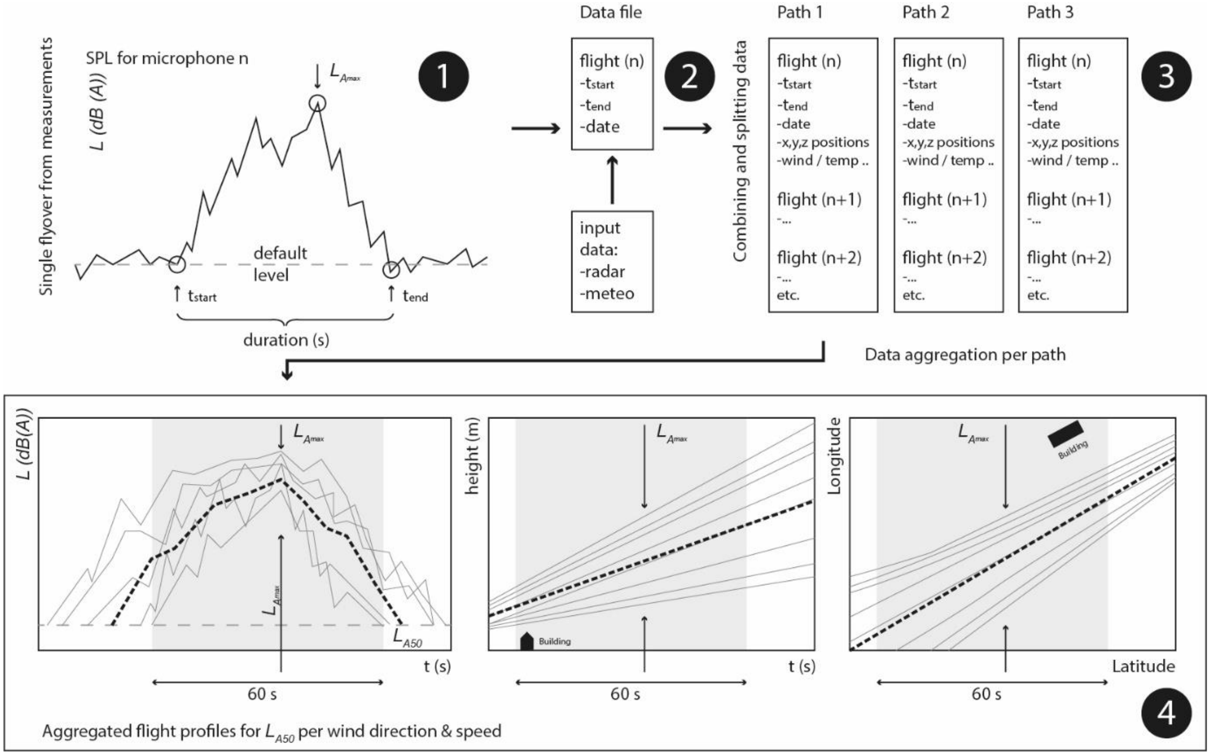

Figure 29 Signal processing in four steps: 1) isolating individual aircraft flyovers, 2) combining acoustic data with ADSB and weather data, 3) dividing data in groups depending on wind speed / direction and 4) aggregating data for each group. The figure illustrates the procedure for eight hypothetical aircraft flyovers.

5.3.2.1. Signal processing

Sound was recorded by using six calibrated microphones (B&K type 4189-A-021) connected to two NI USB-4431 devices (resolution was set at 44.1 kHz) and two laptops (three microphones per USB device; one USB device per a laptop). Each microphone was placed on a tripod 1.5 meters above the ground and 1.5 meters away from the facade. Recordings were carried out during the daytime and the early evenings. The start of each recording was marked by a short and loud sound signal to synchronize data sets from the two laptops. Separate data sets were merged to one matrix in MATLAB using the markers and default time labels attached to the individual files.

The Fourier transform was applied to the sound signal for each microphone with a Hann window for the time interval of interest. The time interval was 1 second for all analyses, except for a regression analysis on the relation between aircraft position and the sound level around buildings. For this analysis the time interval was 3 seconds, to match the resolution of the ADSB data. Sound levels were expressed per 1/3 octave bands, with centre frequencies between 50Hz and 10000Hz.

5.3.2.2. Identification of aircraft flyovers

In the second step, sound from aircraft flyovers was detected and cut from the recordings. The OASPL graph for the *d*LOS microphones closest to the flight path was plotted and aircraft flyovers were selected by visual and auditory screening (i.e. manually). In most cases, aircraft induced peaks were recognizable by a sudden increase of the sound pressure level rising to a peak level, followed by a gradual decay of the sound (see Figure 29 Frame 1). Aircraft flyovers can be divided in three phases: the moment the OASPL starts to increase (t_{start}), the maximum OASPL (L_{Amax}), and the moment the OASPL returns to the initial sound level (t_{end}). Literature often refers to ISO 20906 for aircraft flyover recognition. The ISO directive states that aircraft flyovers are recognized as such when the L_{Amax} level exceeds the normalized OASPL by more than 10dB(A)[43,45]. In this study, the ISO 20906 standard was not followed for two reasons. Firstly, the difference between L_{Amax} levels and the ambient sound level was often lower than 10dB(A), especially for location B and C. Secondly, there was a chance that peak levels had been contaminated by sound from other sources. The research team identified these by listening to the recordings of individual aircraft flyovers and excluded the contaminated recordings. Therefore, the first step was to look at the plots and select t_{start} and t_{end} for each aircraft flyover (Figure 29 Frame 1). WAV files were played and evaluated to ascertain that sound peaks neither originated from e.g. HVAC units, cars or humans nor did they overlap with sounds from any such sources. A MATLAB code was written to cut the aircraft flyover from the data-set, using the t_{start} and t_{end} tags (Figure 29 Frame 2). The aircraft flyovers were saved as separate files labelled with t_{start}, the duration (in seconds) and date in the file name. In total 894 flyovers were recorded, of which 215 were deemed suitable for further analysis. Aircraft flyovers were predominantly dismissed because other noise sources were audible in the sound file.

5.3.2.3. *Ambient sound levels*

Table 2 L_{Aeq} during intervals between aircraft flyovers for all locations and microphones. The total duration of the recordings was 149 minutes for location A, 164 minutes for location B and 298 minutes for location C.

	Microphone 1	Microphone 2	Microphone 3	Microphone 4	Microphone 5	Microphone 6
Location A	59.8 dB(A)	53.4 dB(A)	53.0 dB(A)	60.5 dB(A)	52.3 dB(A)	
Location B	55.4 dB(A)	50.3 dB(A)	51.8 dB(A)	48.8 dB(A)	51.7 dB(A)	49.6 dB(A)
Location C	52.4 dB(A)	51.3 dB(A)	52.4 dB(A)	51.6 dB(A)	50.3 dB(A)	

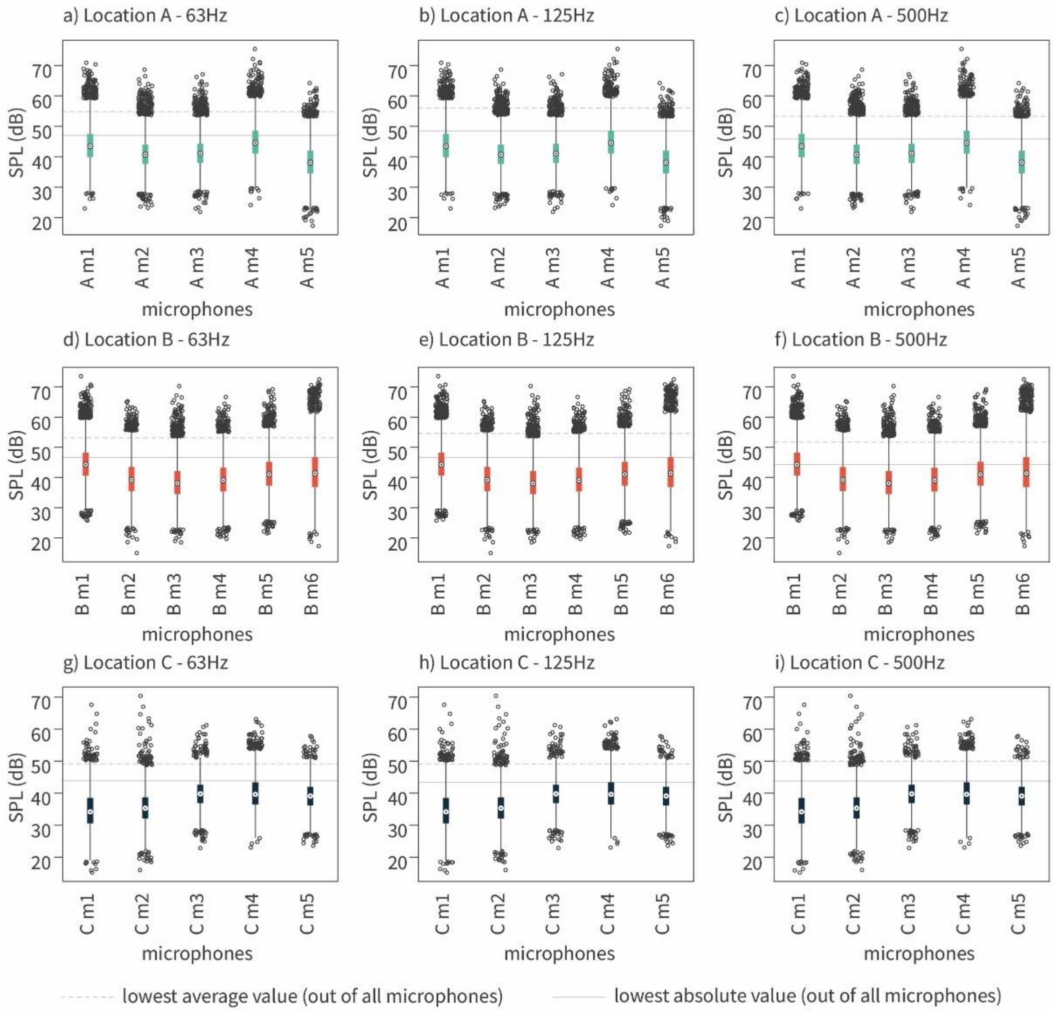

Figure 30 Tukey boxplots showing the distribution of the sound pressure level per microphone (FFT resolution: 1 second) for the 63Hz, 125Hz and 500Hz 1/3-OB. The whiskers range maximum is 1.5 times the interquartile distance from the maximum and minimum values of the box. Values not fitting within the 1.5 times interquartile range are marked as outliers. The grey dotted line shows the lowest average, with the grey solid line showing the lowest threshold (excluding outliers) for L_{max} values per 1/3-OB as recorded for each site (see Figure 37). Outliers accounted for less than 0.5% of the data.

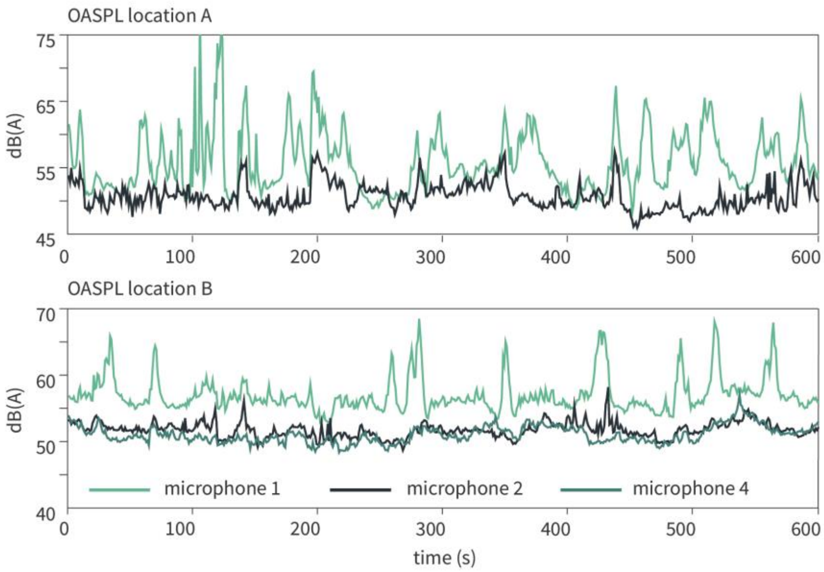

Figure 31 OASPL graphs microphones 1 and 2 during intervals in between aircraft flyovers for location A and B

The chance that recordings were influenced by the presence of any unforeseen acoustic differences was further reduced by comparing the average sound level (L_{Aeq}) between microphones during the intervals in between aircraft flyovers. Although the aircraft flyovers were screened for irregularities in the previous step, the screening had only been performed for one microphone per location.

Table 2 shows the OASPL values per microphone as recorded during the intervals between aircraft flyovers cut from the data. Additionally, Figure 30 shows the distribution of the sound pressure level (per second) for the 63Hz, 125Hz and 500Hz 1/3-OB. The values in the table are the average sound levels of the data per location combined from multiple days. This means that the data was combined regardless of differences in the weather on individual days, although variations in temperature and wind were small (see 5.3.2.4). The table shows that at locations A and B, OASPL levels for microphones close to roads were higher than for the other microphones. Also, the data suggests that the sound pressure level near microphone B2 was louder than near the other *n*LOS microphones B4 and B6. To study this in more detail, 600 seconds was selected out of the data sets for location A and B, and was used to calculate and plot the OASPL. As can be seen in Figure 31, the sound level is higher for microphones A1 and B1 due to short peaks caused by car traffic and passers-by. The graph for microphone B4 follows a trend similar to that of microphone B2. Therefore, the difference is attributed to the noise from cars, as the microphone is closer to the main road than the other *n*LOS microphones. For the files containing aircraft flyovers, the microphones A1, B1 and C1 were controlled for car traffic and passers-by. Since the L_{Aeq} levels gave no reason to check other microphones for irregularities, no further manual analysis of the microphones was carried out except for those near roads.

5.3.2.4. ADSB positions and weather data

Table 3 Weather data for the relevant measurement days per location. [1]Refers to aircraft following direction 2, [2]refers to aircraft following direction 1, [3]refers to aircraft following direction 3, [*]refers to total number of flights and [**]to the numbers of flights that could be matched with ADSB data.

Locations	Hourly wind speed range	Hourly wind direction (range)	Number of flights	Temperature range (day average) (C°)	Humidity range (day average) (%)	Air pressure range (day average) (hPa)
A[1]	7 – 9 m/s	240-260°	67* / 53**	18.2 – 18.5	76 – 82	1009.3 – 1018.9
B[1]	9 – 10 m/s	230°	18* / 18**	17.0 – 19.2	70 - 84	1008.0 – 1020.2
B[3]	9 – 10 m/s	230°	21* / 21**	17.0 – 19.2	70 - 84	1008.0 – 1020.2
C[1]	6 – 7 m/s	220-230°	32* / 31**	18.3 – 21.8	78 – 83	1010.9 – 1021.9
C[2]	6 – 7 m/s	220°	30* / 19**	18.3 – 21.8	78 – 83	1010.9 – 1021.9

After separating aircraft flyover from the overall sound data, the individual files were matched and combined with meteorological and geo-positional (ADSB) data. ADSB was provided by the Netherlands Air Traffic Control (LVNL) and contained the geo coordinates (ground track) and altitude (resolution 3 seconds) of all air traffic near Schiphol airport for the relevant days. The information was used to divide aircraft flyovers in separate groups, based on the flight direction (see Figure 27 and Figure 29 Frame 3). Subsequently, these groups were further divided into subgroups with a similar wind velocity and direction profile. Data was not clustered around temperature or humidity variations, as the estimated effects of these factors on sound dispersion are smaller than i.e. the effects of wind[46,47]. As measurements took place during the same time of the day and during the same season, it was assumed that temperature could be neglected as determining factor. The weather data was derived from open source meteorological data or gathered by the Dutch Met Office (KNMI)[48], who operate a weather mast at the airport. The wind mast is positioned 10 meters above the ground, and the temperature sensor 1.5 metres above the ground. The data were based on the average values per hour and matched with the time tags added to the sound data. Table 3 shows the meteorological data and the number of flights for each location measured under similar meteorological conditions. The table shows that the variance in temperature, humidity and air pressure was small. The measurements were taken over a single month to minimise the seasonal variation in wind velocity and wind speed. The variation in weather types is small, partly because only take-offs from one runway and in one direction were analysed. For a few flights, the wind direction and wind speed clearly deviated from the mean. However, the number of these was too small for additional statistical analyses and so they were dismissed. In the end, one group was analysed for each flight direction (see Table 3).

5.3.3. Analyses

5.3.3.1. Time variance and spectrum

The variance of the sound pressure level during an aircraft flyover was studied in two ways. Firstly, the OASPL graphs and spectrograms of randomly selected flights were studied. Secondly, the mean sound level per flight direction was calculated, to study general trends across the flights. The mean was calculated by identifying the time position of the L_{Amax} for each flight (see Figure 29 Frame 4). Because the duration of aircraft flyovers varied, the research team decided to align the L_{Amax} time positions of the flights within the groups as of Table 3. The combined acoustic data of all aircraft flyovers radiates out from this central L_{Amax} position, as seen in Figure 29 frame 4. The distribution of the aggregated data depends on the extremes in the underlying data. This means that the aggregated sound level at a time $L_{Amax} - t$, representing the distribution of data around the L_{Amax}, is defined by a smaller number of flights when t increases. Therefore, the time window of 60 seconds around the L_{Amax} was analysed (see Figure 29).

$$L_{A50}(t) = \frac{1}{n}\sum_{i=1}^{n} L_{A(i)}(t) \tag{5.1}$$

Equation 1 presents the aggregation protocol, in which $LA_i(t)$ refers to the A-weighted sound level for a flight i for a moment (t) in seconds at the time interval between the minimum and maximum position for the range of all aggregated flights combined. $L_{A50}(t)$ refers to the aggregated A-weighted sound pressure level for moment (t) in seconds at the time interval between the minimum and maximum extremes of the aggregated data. From the $L_{A50}(t)$ different flight paths can be derived, e.g. ΔL_{A10} and $\Delta L_{A90}(t)$.

5.3.3.2. Maximum noise levels around buildings

The distribution of L_{Amax} values was studied for each microphone, in terms of the OASPL and the L_{max}, for three 1/3-octave bands (63Hz, 125Hz, 500Hz). The distribution of the values was studied and compared to the 65dBA threshold from literature.

5.3.3.3. Average noise reduction by buildings

The second part of the analysis focused on the difference between the average A-weighted sound levels during a flight event (L_{Aeq}) per microphone. The L_{Aeq} is calculated with the following equation:

$$L_{Aeq} = 10log_{10}\left(\frac{1}{n}\int_{0}^{n} 10^{\frac{L_p(t)}{10}} d(t)\right) \tag{5.2}$$

The time length n refers to the duration of a flyover in seconds (typically around 60-70 seconds) and $L_p(t)$ to the A-weighted sound level over 1 second. Per flight event, the sound exposure levels for the pairwise *d*LOS and *n*LOS microphones were subtracted according the following equation:

$$\Delta L_{Aeq} = L_{Aeq_{dLOS}} - L_{Aeq_{nLOS}} \tag{5.3}$$

Here, the difference between pairs of exposed (*d*LOS) and non-exposed (*n*LOS) microphones were studied. A pair was formed of two microphones that correspond to the same building (see Figure 27). As the ΔL_{Aeq} is independent from the source power level, results from individual flights are comparable and general trends could be studied. Like for the distribution of L_{Amax} values, results per pair (i.e. per building) were plotted in whisker boxplots. The distribution of the results was analysed according to the definition of quiet sides, i.e. $\Delta L_{Aeq} > 10$ dB. For the L_{Amax} and ΔL_{Aeq} analyses, data was studied per location and flight direction for each of the groups, as in Table 3.

5.3.3.4. *Relationship between source position and noise reduction*

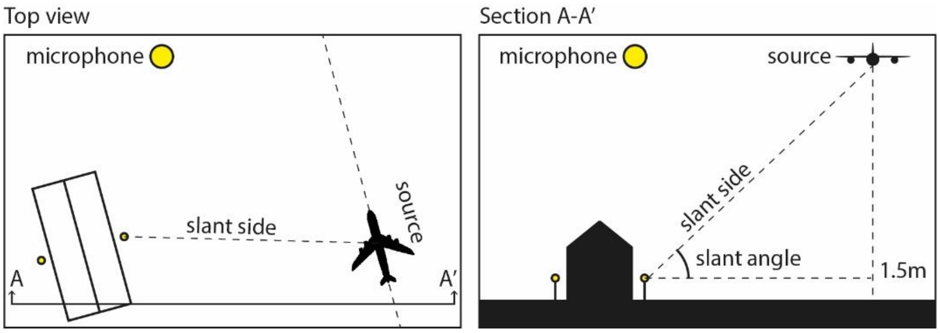

Figure 32 Two imaginary microphones around a building and the slant side calculated between an aircraft and the location. The slant angle and path length are based on a straight line between the first microphone and the position of the source (x, y, z).

The last part of the analysis focused on the relationship between the angle of incidence and the sound reduction (ΔL_{Aeq}) by buildings. Instead of using the aggregated data and the mean sound pressure level, the ΔL_{Aeq} was calculated for each position (in time) for each aircraft flyover. Here, the angle of incidence is defined as the slant angle between the position of an aircraft and the location A, B or C. The microphone closest to the flight path represented the coordinates of the location, see Figure 32. By taking the slant angle as the angle of incidence of the sound front, wave refraction due to atmospheric effects was discounted. The first objective of the analysis was to study the percentage of variance in noise reduction that was explained by the position of the source. The hypothesis was that source position correlates with noise reduction. The second aim of the analysis was to study if building shape and height would result in different model fits. The variance in model fits per location contributes to the hypothesis that shape and form influence sound reduction around buildings. Both hypotheses were tested by a series of linear and polynomial regression analyses. Due to the resolution of the ADSB data, i.e. the data contains the position of the aircraft per 3 seconds, a second Fourier transform was applied to the sound signal for each flight and microphone with a Hann window of 3 seconds. Separate analyses were carried out for straight and curved flight paths, direction 3 for location B and direction 1 for location C respectively (see Figure 27).

5.4. Results

5.4.1. Time variance and spectrum

5.4.1.1. Spectrum

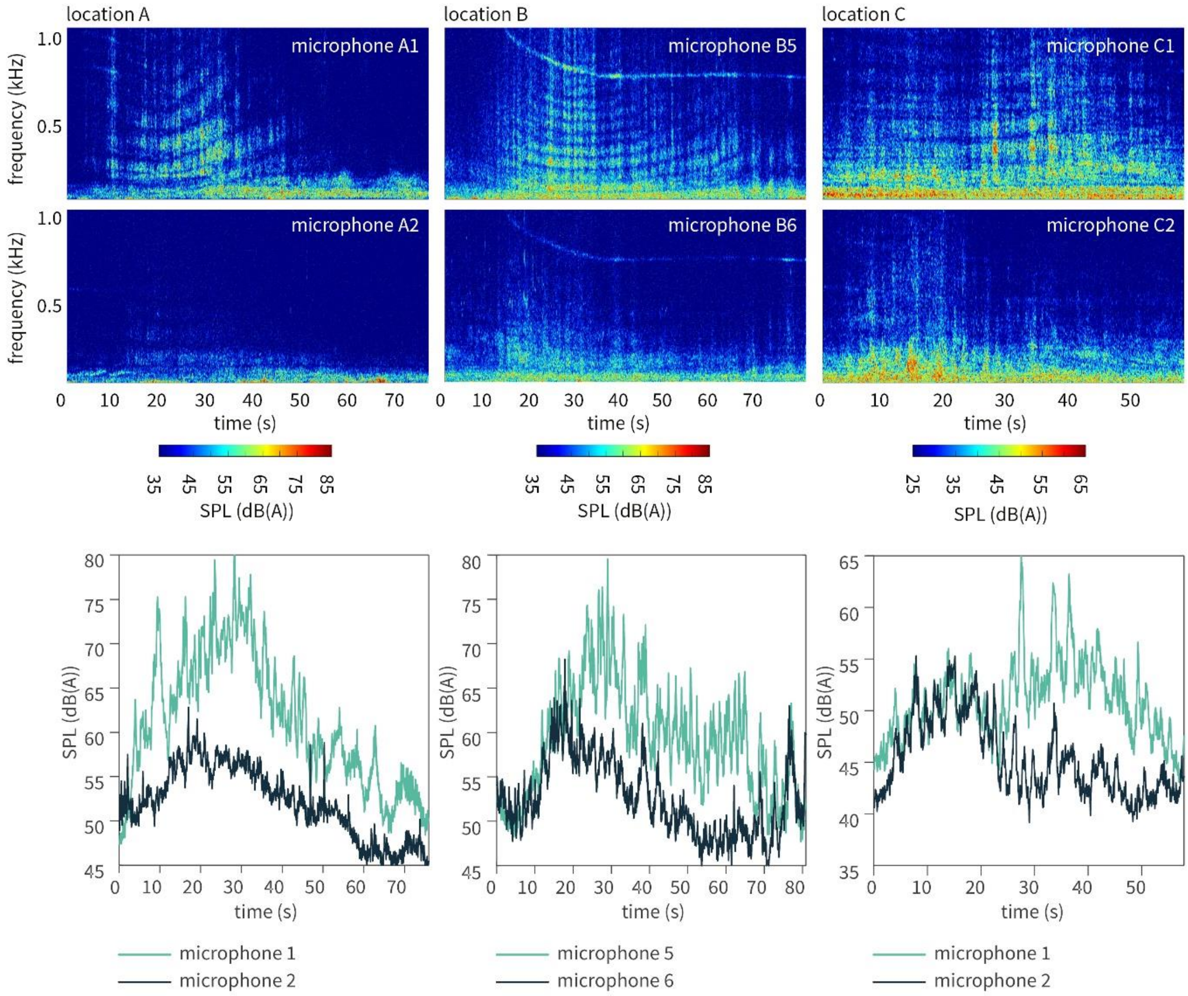

Figure 33 Spectrograms and OASPL for location A (B738 aircraft, flight direction 3), B (B77-L aircraft, flight direction 2) and C (B738 aircraft, flight direction 1).

Figure 33 shows three spectrograms and OASPL graphs for three representative pairs of *d*LOS-*n*LOS microphones, one for each flight direction and location. The spectrograms suggest that sound energy declines over the full domain between 0 and 1000Hz. However, the sound energy decays more markedly for frequencies above 250Hz compared to frequencies below this level. Tonal shifts (Doppler effects) are visible for microphone A-1 and B-5 but are almost unnoticeable in the spectrograms for microphones A-2 and B-6, as Doppler predominantly distorts higher tones. The graph also illustrate the presence of propagation effects, such as 1) turbulent spectral broadening, and 2) effects of turbulence and wind-gusts[38,49]. The first refers to tonal sound energy distributed to surrounding frequencies during propagation. This is visible as the horizontal bands or brushes in the spectrograms of the *d*LOS microphones (A-1, B-5, C-1). The second are local and sudden variations of the sound energy, attributed to turbulence and wind-gusts, which are visible as vertical lines in the spectrograms. Since higher pitches are more sensitive to both atmospheric effects and noise reduction by buildings, what remains is a low frequency rumble at the *n*LOS positions (see the blue lines in the OASPL figures).

5.4.1.2. Time variance (straight aircraft flyovers)

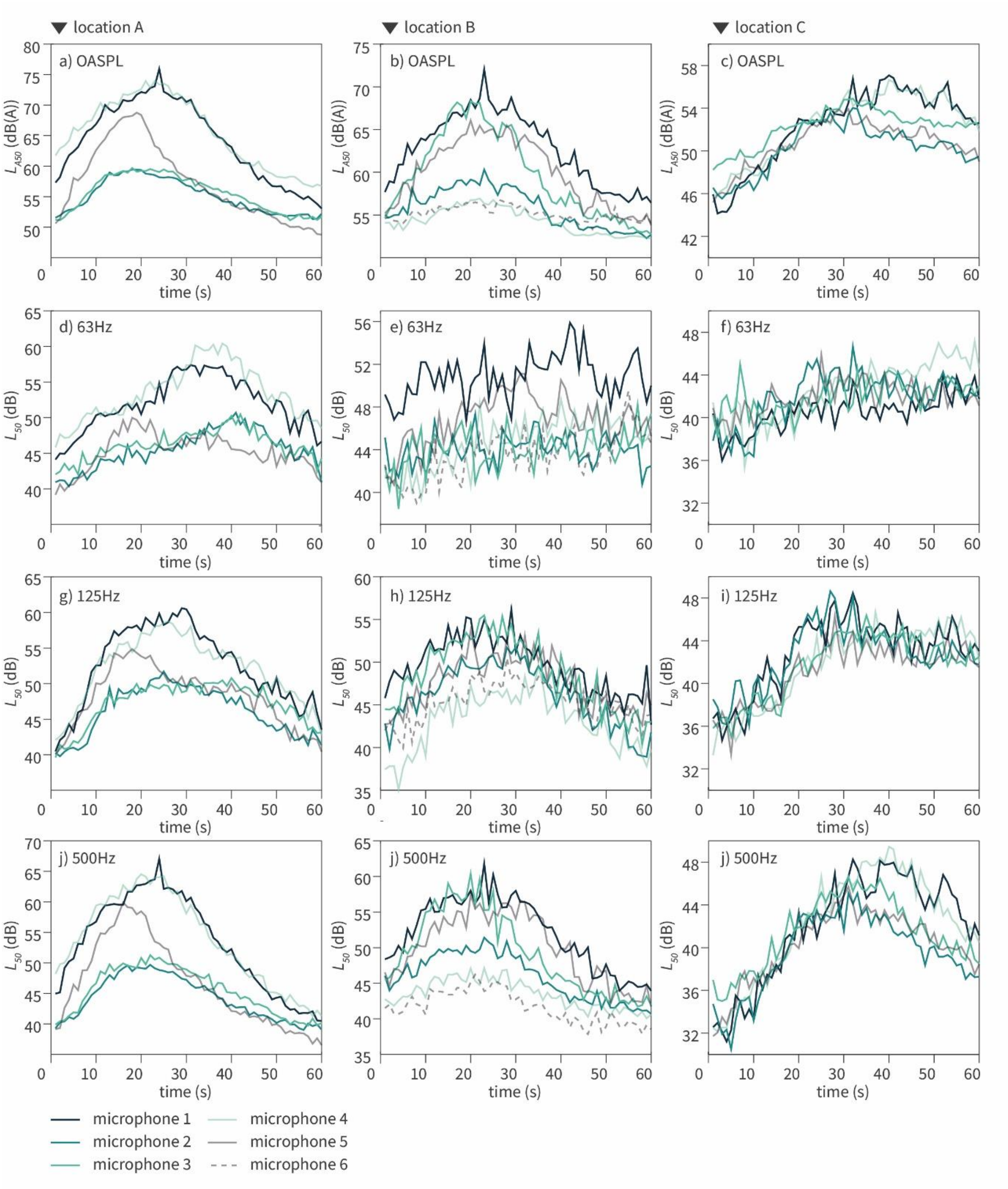

Figure 34 L_{A50} for straight flight paths (following direction 2 in Figure 27Figure) from the aggregated data for each location. Results for 60s window around the L_{Amax} are given, plotted per 1s.

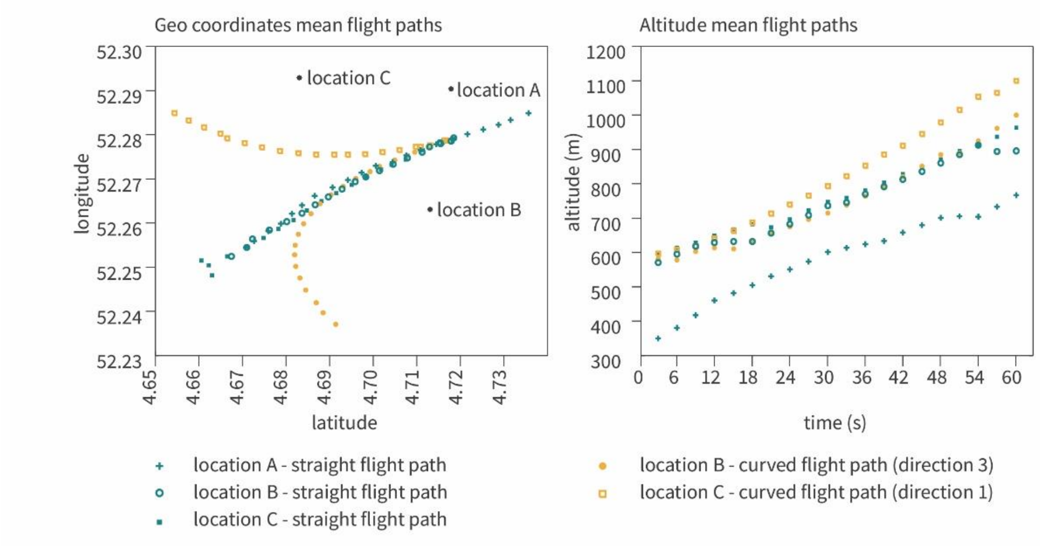

Figure 35 Mean geo coordinates and altitudes for straight and curved flight path combined. The figures correspond to the L_{A50} levels in Figure 34 and Figure 36. Results for 60s window around the L_{Amax} are given, results are plotted per 3 seconds.

Figure 34 shows the mean sound pressure level per second of the aggregated data for all microphones ascending in a straight line from the runway. The graphs show results for a time window of 60 seconds around the L_{Amax} positions. Results for the OASPL and the 63Hz, 125Hz and 250Hz 1/3-octave bands are given in both figures. In Figure 34, the difference between *d*LOS and *n*LOS microphones is clearly visible in the OASPL graphs. However, in the graphs per 1/3-OB, this difference is only noticeable for all three frequencies at location A. The L_{A50} graphs for the 500Hz 1/3-OB and OASPL follow a similar trend due to the A-weighting. Like the spectrograms, Figure 33 confirms that, except for location A, buildings mainly reduce sound energy for higher frequencies. However, caution should be observed in respect to the interpretation of the results, as for location B and C the sound level of the aircraft flyovers is close to the ambient sound level (see Figure 30). Although the peak levels are clearly higher than the ambient sound level for all 1/3-OBs that were analysed, the background noise might (partly) mask the sound signal of the aircraft flyovers. Essentially, this means that the duration of the flyover that can be measured is shorter for location B and C than for location A, which affects the L_{Aeq} graphs for location C. Figure 33 also shows a clear contrast between the results for the *n*LOS microphone A-5 and microphones A-2 and A-3. The sound level at microphone A-3 rises in a similar way as microphones A-1 and A-4 during the first 20 seconds, but drops between 20 and 30 seconds, before continuing at the same level as the other *n*LOS microphones after 30 seconds. This is likely caused by the shape of the building that stands in between microphone A-4 and A-5. Figure 27 and Figure 28 show the L-shape of the building and the different heights for the facade facing towards microphone A-4 and the facades near microphone A-5, which is much lower. This means that the microphone is further from the tallest facade than the other *n*LOS microphones. However, when the aircraft fly away from the location, microphone A-5 is shielded by the taller facade closest to the microphone. Figure 34-b shows a similar effect of the built-up context around microphone B-3. While the graph follows the trend of the other *d*LOS microphones B-1 and B-5, the sound decays faster at microphone B-3 during the last stage of the aircraft flyovers. Because the sides of the building provide shielding, the sound reaching the microphone is diffracted and scattered by the flanks of the building. Consequently, the sound recorded by microphone B-3 faded away faster than for microphones near facades without bays. This means that the duration of the sound event is shorter.

5.4.1.3. Time variance (turning aircraft flyovers)

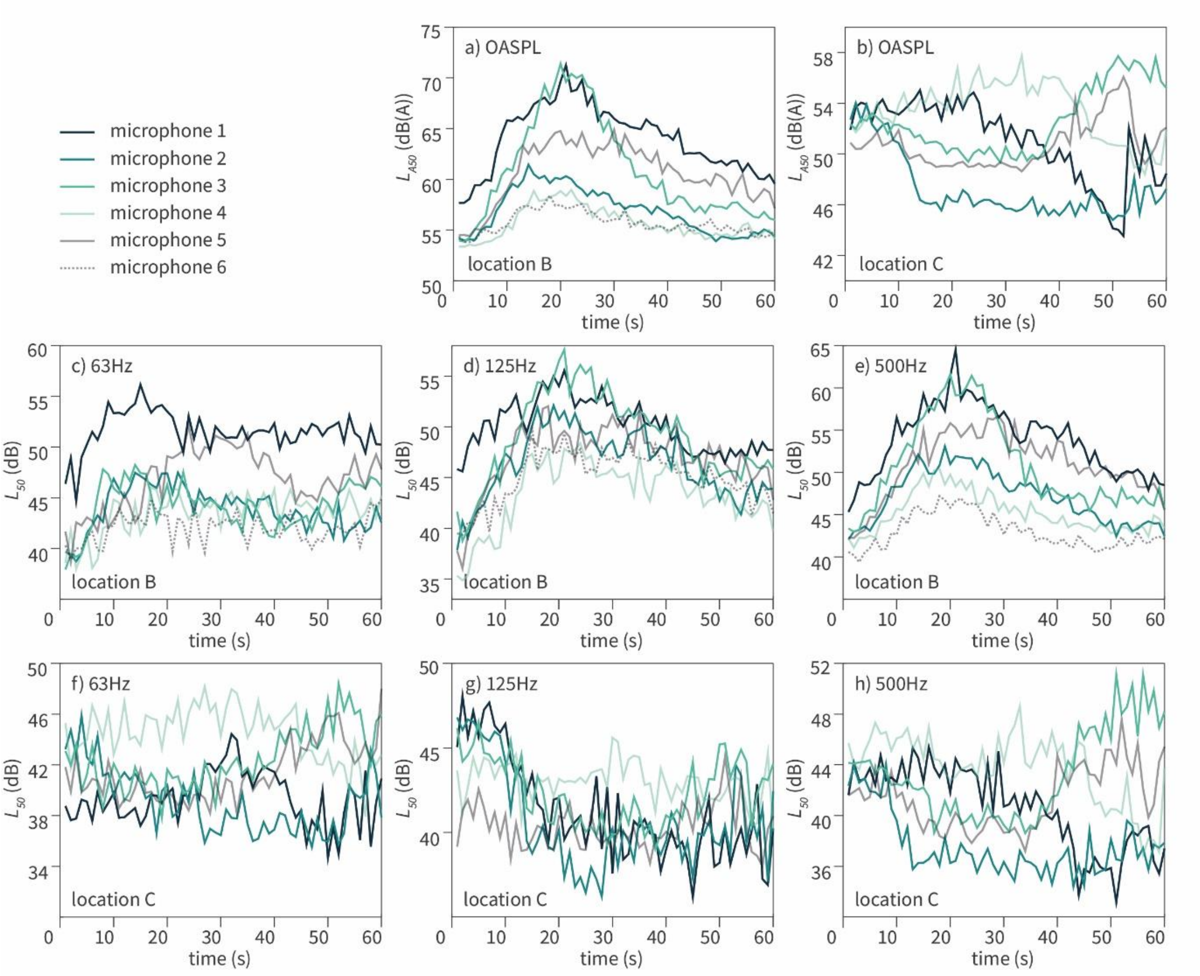

Figure 36 L_{A50} for turning flight paths (following direction 2 in Figure 27) from the aggregated data for each location. Results for 60 seconds window around the L_{Amax} are given, plotted per 1 second.

Figure 36 shows a different pattern for turning aircraft above location B and C. For location B, there is minimal difference in the variance in the sound level for aircraft flying a straight flight path or turning to the east. Figure 36-b indicates that this is not the case for location C. Based on the geo-coordinates shown Figure 35, the difference between locations B and C is attributed to a difference in curvature profiles of flights following direction 1, versus aircraft turning to direction 3. While the mean flight path in direction 1 turns gradually, aircraft flying in direction 3 keep to a straight path for much longer, before making a sharp bend to the east. This means that the aircraft rotate their engines away from location B, thereby reducing the sound energy emitted towards the location. When aircraft turn towards direction 1, the curve is smoother and less abrupt, and the aircraft will only slightly turn their wings and engines. In other words, the aircraft will radiate the sound in a direction comparable to that of a straight flight path. However, the figure shows that the side of a building with a *d*LOS and *n*LOS reverse once the aircraft flies by. As for straight flight paths, Figure 36 shows that buildings reduce aircraft noise more effectively for frequencies above 500Hz.

5.4.2. Maximum noise levels around buildings

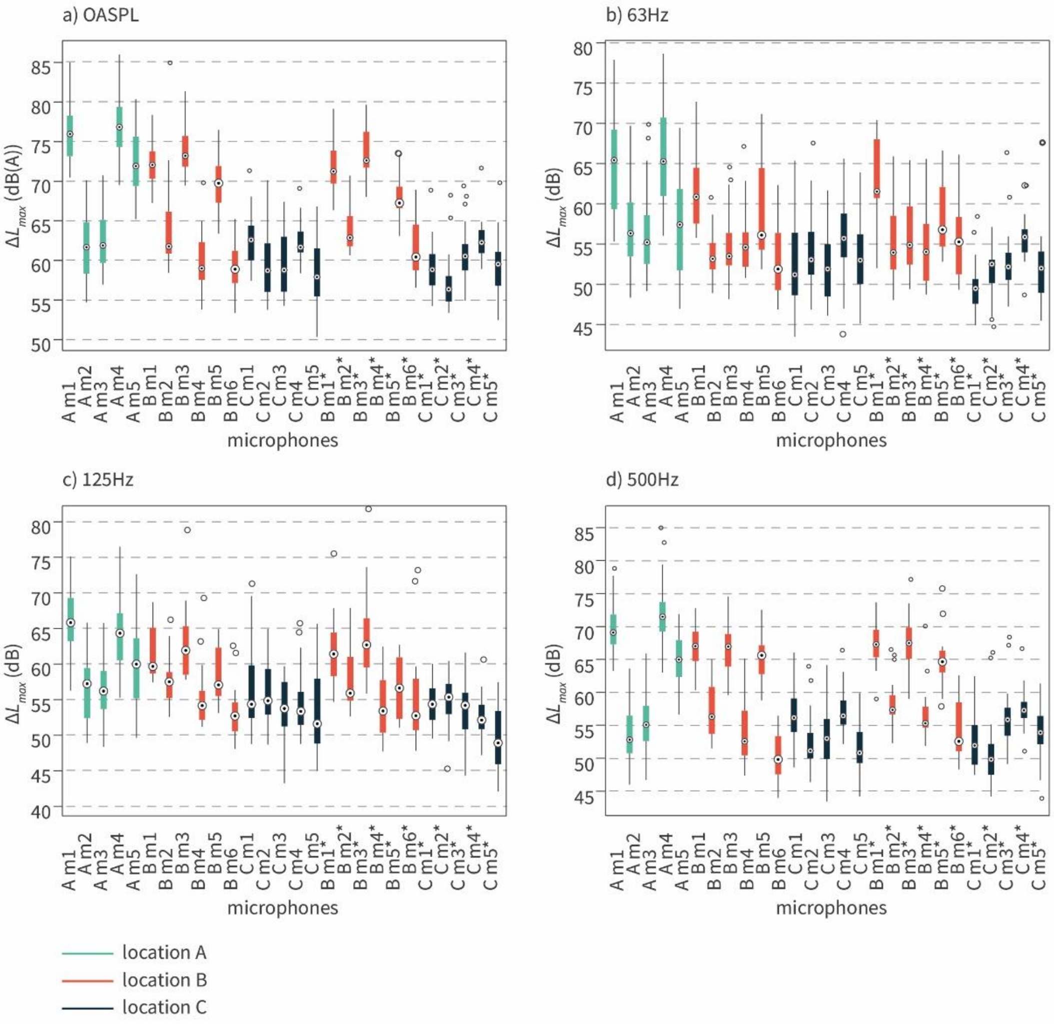

Figure 37 Tukey boxplots showing the distribution of L_{Amax} levels per microphone (FFT resolution: 1 second). The whiskers range maximum is 1.5 times the interquartile distance from the maximum and minimum values of the box. Values not fitting within the 1.5 times interquartile range are marked as outliers.

Figure 37 shows the distribution of the maximum sound levels (L_{Amax}) per microphone for the OASPL and for the 63Hz, 125Hz and 500Hz 1/3-octave bands. Figure 37-a shows that the mean L_{Amax} levels of microphones A-1, A-4, B-1, B-3 and B-5 all exceeded 65 dB(A) (all *d*LOS positions). The figure also shows that none of the mean L_{Amax} values for any of the *n*LOS microphones was above 65 dB(A), except for microphone A-5. For a straight flight path, most of the mean L_{Amax} levels for *n*LOS positions were below 60 dB(A), especially for location C.

5.4.3. Average noise reduction by buildings

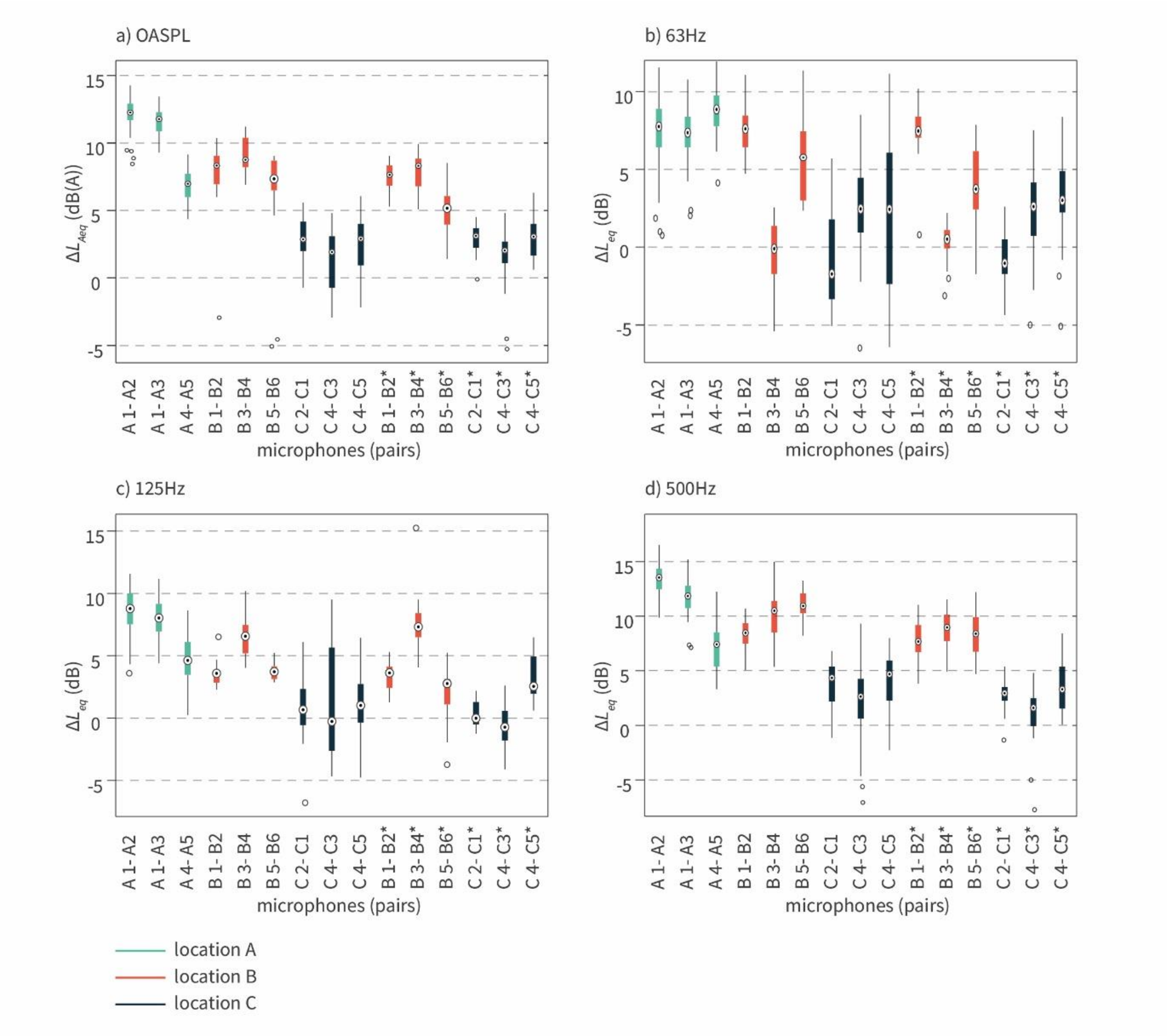

Figure 38 Tukey boxplots showing the distribution of ΔL_{Aeq} levels per microphone (FFT resolution: 1 second). The whiskers range maximum is 1.5 times the interquartile distance from the maximum and minimum values of the box. Values not fitting within the 1.5 times interquartile range are marked as outliers.

Figure 38 shows the distribution of the average noise reduction (ΔL_{Aeq}) around the buildings concerned. The figure shows that the mean noise reduction during an aircraft flyover varied between 2 dB(A) (location C) and 12dB(A) (location A). The buildings furthest from the flight path, i.e. location C, reduced noise least effectively. The mean noise reduction during a flyover only exceeded 10dB for the building surrounded by the A-1, A-2 and A-3 microphones. Figure 38b-d illustrates that buildings reduce aircraft noise for all the 1/3-octave bands concerned. However, the difference in noise reduction for exposed versus non-exposed building sides grows larger as the frequency increases. For location A, the results show a clear difference between the two buildings at this location. Compared to the microphone pairs A1-A2 and A1-A3, the noise reduction by the building in between pair A4-A5 is lower, especially for 1/3-octave bands >125Hz. In addition, Figure 38b shows that, for 63Hz, the noise reduction between the microphones B3-B4 is less than for the other buildings at location B. Comparing the sound levels as recorded by the microphones B1,B3 and B5, the levels are lower for microphone B3 than the other two. This results in different degrees of noise reduction as measured around the three buildings at location B (see Figure 37-b), although this effect is mainly visible for the 63Hz 1/3-OB. This difference can be attributed to the directivity profile of aircraft noise, as the lower frequencies are emitted behind the engines. Based on the directivity vector of aircraft noise, this results in conically shaped profile. This means that the waves containing the lower frequencies reaches microphone B3 from aside, with the flanks of the building shielding the microphone from direct exposure. This negates the differences between microphones B3 and B4, at least for the 63Hz 1/3-OB. Another observation is the relatively large distribution of data for the pair of microphones C-4- C-5 in Figure 38-b. Likely, the data in this figure is contaminated by flyovers turning to the west, especially when a preceding aircraft is relatively loud or close. As lower frequencies are less sensitive to atmospheric absorption, and distributed in a conical shape behind the aircraft, the rumble of the engines follows last. However, as the flight peaks were isolated and cut from the data-set based on the A-weighted sound pressure level, this ‘tail’ is not clearly visible in the graphs.

In general, Figure 38 shows that the noise reduction yielded by buildings is larger for location A than B, and especially C. Meakawa’s[35] barrier model gives a theoretical basis to explain this difference through the Fresnel number N, which is described by the following equation:

$$N = \frac{2\delta}{\lambda} \tag{5.4}$$

With the path length between a source and receiver via a barrier δ and the wave length λ. The Fresnel number gets smaller for greater path lengths, or smaller wave lengths, which results in a smaller noise reduction around the barrier. The propagation path between the aircraft and the buildings is greater for location C than for location A and B, hence the buildings provide less shielding. The equation also explains the differences between Figure 38b-d.

5.4.4. Relationship between source position and noise reduction

5.4.4.1. Straight aircraft flyovers

Table 4 Results of the first order polynomial regression analysis with the dependent factor 'noise reduction' (ΔL_{Aeq}) and the independent factor 'slant angle' (◦), both indicated as the factors b1 and b2. Results are given per pair of microphones (see Figure 28) and for aircraft flyovers in direction 2 (see Figure 27).

Model fit	Pairs of microphones								
	A 1-2	A 1-3	A 4-5	B 1-2	B 3-4	B 5-6	C 1-2	C 4-3	C 4-5
Constant	-6.508	-6.316	3.723	1.792	-5.679	-7.176	7.994	4.756	7.025
*b*1	1.685	1.619	.685	.183	.682	.749	-1.302	-1.127	-1.285
*b*2	-.039	-.038	-.023	.002	-.007	-.010	.063	.058	.085
df	2,1059	2,1059	2,1059	2,387	2,387	2,387	2,668	2,668	2,668
F	158.614	171.009	16.333	77.425	80.035	49.915	19.885	22.035	24.399
R^2	.231	.244	.030	.289	.293	.205	.056	.062	.068
p	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001

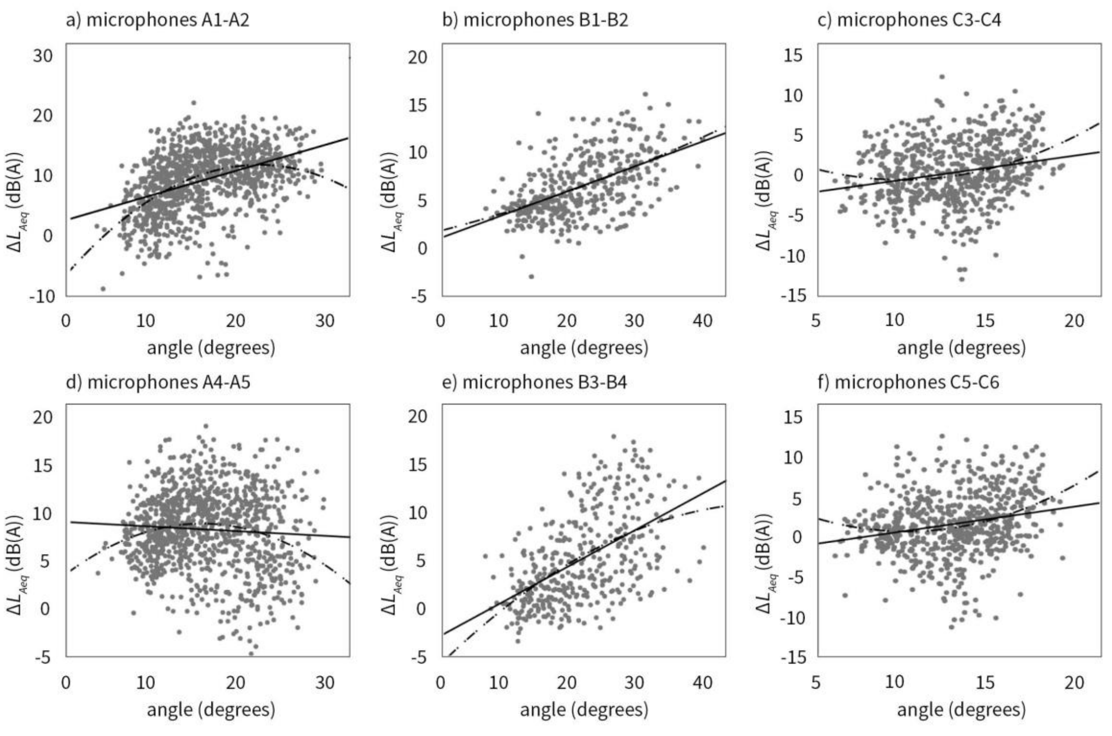

Figure 39 Scatter plots and regression lines for six cases representative of the variance between buildings in terms of the aircraft noise reduction as shown in Table 4. Two buildings are plotted per location.

The relationship between the source position and noise reduction was studied by means of regression analysis. Literature shows that buildings directly underneath flight paths barely abate aircraft noise. However, the results in the previous sections show that the noise reduction yielded by buildings decays with the (horizontal) distance from the flight path. This suggests that the level of reduction, as induced by buildings, varies in a curvilinear way with a maximum positioned in between two zeros (i.e. no difference between exposed and non-exposed building sides). Hence, the results of a first-order polynomial regression were calculated and analysed.

A first analysis of scatter plots of the data suggested a non-linear relationship between noise reduction around buildings and the slant angle. This is also plausible from a theoretical perspective, as literature shows that building geometry has little effect on aircraft noise abatement when the horizontal distance to flight paths is small. Hence, this suggests that there is an optimum angle for noise reduction. Angles that are too large or too small will reduce the noise-attenuating effect of buildings.

Table 4 shows the results for the first order polynomial regression analyses per pair of microphones. The independent variable ‘slant angle’ is represented by the factors b1 and b2, inherent to the mathematical description of a polynomial regression model. Second and higher order polynomial regression models were also significant for most buildings. However, since trend lines were much harder to interpret or were incompatible with theory, and results were often close to those for the linear or quadratic models, only results for the first order regression models were analysed. Table 4 shows that for all the locations, there was a significant non-linear (quadratic) relationship between the noise reduction and slant angle. However, the predictive power of the slant angle (as a variable) varies between buildings and is lower for location C than for location A and B. The table shows that microphones placed around buildings with a similar shape, such as microphones A1-A2 and A1-A3 or B3-B4 and B5-B6, yielded comparable results. This indicates that building shape and surface impedance are important for the noise level around a building. The difference between the buildings at location A and the buildings in between microphones B3-B4 and B5-B6 would confirm this observation. Variations between the buildings were studied by means of scatter plots in Figure 39. Figure 39a and Figure 39d also clearly show the difference between the two buildings at location A. The contrast between them is attributed to the variation in building heights around microphone A5. As the slant angle is the product of the flight altitude and the horizontal distance between source and receiver, a large angle could mean that an aircraft climbs at a moderate rate but is still horizontally close to location A. On the other hand, it could also mean that both the altitudinal and horizontal distances between an aircraft and location A are large. Both situations result in the same slant angle, but sound will reach microphone A5 via either the lower or the higher part of the building, which is manifested in the noise reduction measured. For location B, Figure 39 shows that the building in-between microphones B3 and B4 abates aircraft noise more effectively in comparison to the building separating microphones B1 and B2. This can be attributed to the u-shape of the first building and to the impedance of the pasture that surrounds microphone B4. Figure 39 shows that the optimum angle that results in maximum noise reduction varies between different locations and buildings. For location A, the optimum angle is between 20° and 30°, while Figure 39e suggests that this value is >40° for location B.

5.4.4.2. Turning aircraft flyovers

Table 5 Results of the curvilinear regression analysis with the dependent factor 'noise reduction' (ΔL_{Aeq}) and the independent factor 'slant angle' (°). Results are given per pair of microphones (see Figure 28) and for aircraft flyovers turning towards direction 1 near location C, and direction 3 above location B (see Figure 27Figure).

Model fit	Pairs of microphones					
	B 1-2	B 3-4	B 5-6	C 1-2	C 4-3	C 4-5
Constant	-1.181	-8.847	-.333	-13.836	-17.968	10.816
*b*1	.560	.904	.179	1.369	1.741	-1.030
*b*2	-.009	-.013	.000	-.026	-.038	.018
*d*f	2,563	2,563	2,563	2,465	2,465	2,465
F	28.457	58.227	20.971	34.356	15.128	19.190
R^2	.092	.171	.069	.129	.061	.076
p	<.001	<.001	<.001	<.001	<.001	<.001

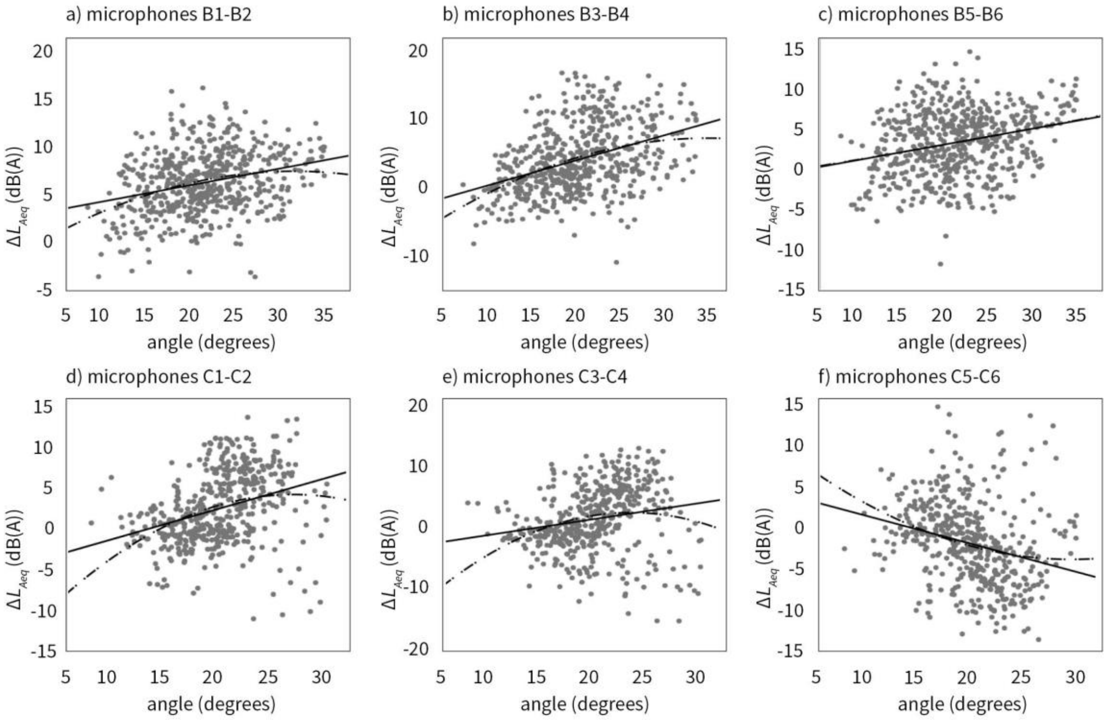

Figure 40 Scatter plots and regression lines for six cases representative of the variance between buildings in terms of the aircraft noise reduction as shown in Table 5. Two buildings are plotted per location.

Table 5 and Figure 40 show the results of curvilinear regression analyses for aircraft turning. For location B, the graphs look like those of a straight flight trajectory, although there are more negative values visible in figures a-c. When aircraft turn near location B, the *d*LOS and *n*LOS microphones will inverse, which was noticeable for microphones B5 and B6. However, the inversion is clearer for location C than for location B, although the mean curvature of both turns looks comparable (see Figure 35). A likely explanation is that the aircraft climb higher as they turn. This means that the sound levels will be lower, as they are only heard on the ground once the turn has been completed and the aircraft resume(s) a straight path.

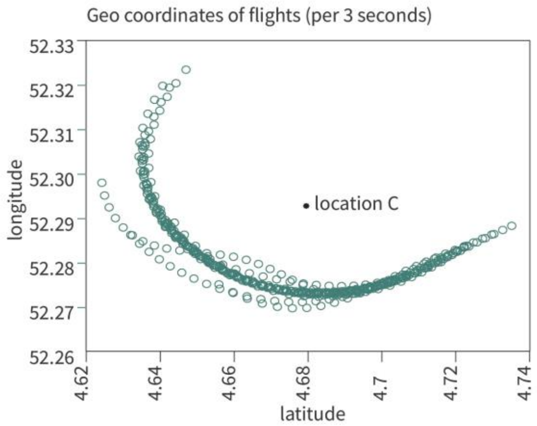

Figure 41 Ground positions over time of flights making a turn in direction 1 around location C (resolution 3 seconds).

The results for location C show a wider spread of data. For larger angles, Figure 40d-f show that the difference between *d*LOS and *n*LOS positions can be either negative or positive. While most of the results indicate positive noise reduction for the buildings surrounded by the microphones C1-C2 and C3-C4, for a small number of flights these results are almost identically negative. This can be explained by Figure 41, which shows that a few flights complete the turn and then inverse *d*LOS and *n*LOS positions equally. Figure 41 also explains why most results are negative in Figure 40f, as aircraft will be loudest once closest to the microphones, which is when an aircraft is (at least) halfway through the turn.

To conclude, Table 4, Table 5, Figure 39 and Figure 40 all show that the majority of the variance in noise reduction cannot be explained by the position of the aircraft alone. Other factors are likely responsible for a large share of the variance, such as wind and temperature variations in the atmosphere, around the source and near the buildings.

5.5. Discussion and conclusions[4]

In this chapter, the results of a series of in-situ measurements studying the reduction of aircraft noise by buildings were presented. The research objectives were:

1. To examine if sound pressure levels vary around buildings exposed to aircraft noise, and to what extent this yields a ‘quiet’ building side.
2. To examine if the position of the sound source and the slant angle predict the difference in sound pressure levels around buildings exposed to aircraft noise.

[4] The discussion and conclusions are combined in one section, as requested by Building and Environment.

Firstly, the results show that buildings reduce aircraft noise, i.e. there is a clear difference between facades which are either in or out of a flight path's direct line of sight (*d*LOS and *n*LOS respectively). However, the level of reduction depends on the horizontal and vertical distance from the source and the shape of (the) building(s) surrounding the receiver. The results show that the difference between *d*LOS and *n*LOS facades is greater when the source is closer to the receiver. The non-linear relationship between the position of the aircraft (slant angle) and noise reduction suggest that the noise reduction peaks when the slant angle is >20°, but decreases when the angle becomes too large. However, the optimal angle resulting in the largest noise reduction varied between buildings and locations, although data extrapolation suggests the maximum angle will be >45° for most locations. In addition, the results show that the noise reduction is greater for tall buildings, and that u-shaped buildings (e.g. with flanks or bays) shorten the duration of exposure.

Secondly, when comparing the study's results with the definitions for quiet facades, the mean noise reduction was well above >10dB(A) for one building (location A). However, this does not necessarily mean that a difference above 10dB(A) will lead to lower annoyance ratings for aircraft noise, as results cannot always be carried across from one noise source to another. Spectrograms and results per 1/3 octave band show that buildings mainly abate sound energy for frequencies above 200Hz. However, the results suggest that taller buildings and buildings closer to the flight paths reduce sound energy for low frequencies effectively too. Maximum noise exposure levels were above 45dB(A) for all microphones, not least because the ambient noise levels alone were above 45dB(A). Except for one microphone, the mean peak exposure levels (L_{Amax}) recorded at *n*LOS positions were well below 65dB(A) and below 60dB(A) in three cases. Based on the results, it can be concluded that buildings can reduce both the peak exposure levels and the duration of exposure.

Finally, the study found a non-linear relationship between the source position and the noise reduction measured around buildings. This means that the position of the aircraft, seen as a straight line between a building and the source, partially explains the variation in noise reduction by a building. For aircraft ascending in a straight line from the runway, the results show that the quadratic regression model explains between roughly 20% and 30% of the variance in noise reduction for location A and B. However, for location C, which had a larger horizontal distance from the flight track, the predictive power was lower (<10%). The model fit is influenced by a building's form and height, which can result in different levels of noise reduction for the same slant angle. The best example of this is the building in between the microphones A4 and A5. The results for turning aircraft show a weaker relationship between source position and noise reduction, partly because the exposed and non-exposed position can inverse during or after the aircraft turn. Further research is needed to identify what impact factors like wind and temperature have on the angle from which sound hits a building on the ground. Studying such effects would require permanent and long-term noise data around buildings, combined with meteorological and ADSB data (see e.g. [50]). To conclude, the results gained from this research can be used to aid urban planning near airports and form a basis for more extensive follow-up research.

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6. A method for the numerical prediction of aircraft noise dispersion around buildings for an inhomogeneous atmosphere[5]

6.1. Abstract

For aircraft noise, existing numerical prediction models are not equipped with algorithms to study the propagation of sound around buildings. Methods such as INM and doc.29, as well as high-fidelity aircraft auralization models, include ground reflections, but neglect wall reflections and edge diffraction. Conversely, it is unclear how fit for purpose urban acoustic models are to simulate aircraft noise, especially when the distance between the aircraft and the receiver is substantial. In this paper, an intermediate between an aircraft auralization and urban acoustic model is introduced and tested. The study used an urban acoustic model with a less detailed mode of simulating refraction than the high-fidelity auralization models. However, comparison of both methods showed that the results agreed well with each other. In a second experiment, the method was compared with aggregated measurements for three urban sites located near a runway. Different speed of sound gradients representing a refracting atmosphere were compared. The results show that simulations are both closer to the measurements for linear gradients between $>0.004s^{-1}$ and $<0.0010s^{-1}$ and also limit the risk that the sound reduction is overestimated. To simulate aircraft noise around buildings, both experiments showed that refraction is important when the angle of incidence is >15 degrees between the source and the receiver, but it can be neglected for smaller values.

6.2. Introduction

Around airports, large areas are exposed to aircraft noise, which has a negative impact on the quality of life and health in these areas. To limit the exposure to adverse sound levels, aircraft noise prediction models are used to calculate the noise levels in areas near flight paths[1,2]. The calculations are turned into noise maps, which are used to impose building restrictions in areas where noise levels are deemed too high. Aircraft noise predicting models, such as INM, AEDT[3] and doc.29[4], predict the average sound level per area based on heuristic data[5]. The average sound level is the summation of the noise footprint of individual flights. To balance between calculation speed and accuracy, the models' resolution, i.e. the distance between grid points, is relatively large[4]. Consequently, only ground reflections and terrain irregularities are included, while buildings and cities are omitted[2,5].

[5] The ambition is to submit this chapter as a journal article to Noise Mapping or Applied Acoustics once chapter 5 has been published.

Figure 42 Contour lines around Amsterdam Airport Schiphol based on calculations. The area in colour is the village of Rijsenhout, exposed to noise from various flight paths[6].

Figure 42 shows the predicted noise levels near one of Amsterdam Airport Schiphol's runways, placed as a layer on top of the map. The image shows the rigidity of the contour lines, cutting through buildings and plots of land, and indifferent to local variations in the urban morphology. However, as the noise maps are used for building regulations, the contour lines have a great impact on architecture and urban planning. For example, Dutch noise legislation strictly limits building activities in the village in Figure 42[7].

More recently, various studies pointed out the influence of buildings and urban form on the propagation of aircraft noise, although the effects vary between locations [8–10]. For areas which are directly or almost underneath flight paths, buildings barely reduce aircraft noise[8,11,12]. But, buildings at a greater horizontal distance from a flight track, e.g. the village in Figure 42, may offer a noise abating effect[9,10]. For instance, a study in Frankfurt found that during an aircraft flyover, sound levels were clearly higher or lower depending on the building side [10]. A computational study showed that, on an urban mesoscale, the sound exposure levels between buildings vary between urban typologies [9]. This means that the design of buildings and streets do in fact influence the sound exposure levels in areas exposed to aircraft noise. However, neither of the two studies scrutinized the contribution of individual building design variables, such as the building height, shape, surface cladding and/or urban density, to the attenuation of aircraft noise. For other traffic sources, such as cars or trains, it is common to use numerical models to study the noise reducing potential of individual or combined design variables. Numerical models are a relatively fast and cheap way to compare design variants under the same conditions. However, it is unclear whether similar numerical models are sufficiently fit for purpose to study the impact of (architectural) design variables in relation to aircraft noise.

Aircraft noise predicting models are either used for noise mapping or auralization[2,13]. For noise mapping, the average noise levels are based on the summation of noise exposure levels per flight[1,5,14]. Aircraft noise auralization models assume a flight path as a sequence of source positions[15]. For each position, the propagation path(s) between the source and the receiver is calculated and used to adjust or synthesize the sound signal[15]. During take-offs and landings, aircraft noise travels through the sky before it reaches the receiver. As the temperature decreases and the wind speed increases with the height, the sky is considered to be inhomogeneous. Volumetric mass differences between air layers lead to refraction of the sound waves. Hence, atmospheric effects will be more pronounced, and become important as the distance between the aircraft and the receiver increases. In order to include these effects in auralization models, Arntzen and Simons [2,15] developed a method to correct the propagation path for weather effects. They showed that refraction becomes important when the angle of incidence is greater than 15°[15]. Despite the fidelity of auralization models, the models only include ground reflections, while edge diffraction and reflections between walls are neglected [2].

On the contrary, walls, reflections and edge diffraction are traditionally studied in urban acoustic models for road or rail traffic [16]. Depending on the scale and objectives, a range of models are available, which vary in accuracy and calculation speed[16,17]. Although some models include aircraft noise simulation packages, the models only implement generic noise prediction methods like doc.29 [18,19]. Hence, the available models do not provide standardized and/or validated modules to simulate aircraft noise around buildings. In the past, (heuristic) urban acoustic models have been used to simulate the propagation of sound emitted by low-flying aircraft around buildings [9,11]. Hoa and Kang[9] simulated a low-flying aircraft as a cylindrically radiating line source and varied the horizontal distance between the flight path and an urban area. Ismail and Oldham[11] simulated a low-flying aircraft as a static spherically radiating source while varying the position of the receiver in a street canyon. Both studies neglected the impact of atmospheric effects and only considered a maximum source height of 400ft (≈123m). This raises the question of to what extent these methods can be used to simulate the propagation of aircraft noise around buildings for a greater distance between an aircraft and a receiver.

This chapter evaluates the use of an urban acoustic model to predict the propagation of aircraft noise around buildings which are located at a substantial distance from a flight path. In this study, a substantial distance is defined as a horizontal distance >200m between a building and the mean ground positions of a flight path and a vertical flight altitude >400ft (≈123m)[9].

The study had the following three objectives:

1. To develop and test an intermediate approach between a high-fidelity aircraft auralization and an urban acoustic numerical model.
2. To define the significance and influence of atmospheric refraction for the prediction of aircraft noise dispersion around buildings.
3. To analyse the difference between a simplified method to calculate atmospheric refraction in an urban acoustic model and in-situ measurements.

The chapter starts with a detailed introduction of the intermediate numerical approach and research methodology. The second part of the paper presents the results of two experiments carried out to test and benchmark the simulation approach, and to define the significance and influence of refraction. The two experiments are compared with literature in the discussion section. The paper closes with the findings and conclusions.

6.3. Methodology

6.3.1. Simulating aircraft noise

Traditionally, low-flying aircraft flyovers were simulated as a spherically radiating line[9] or a (single) point source[11] in studies analysing the propagation of aircraft noise around buildings. The studies neglected atmospheric refraction. Aircraft auralization models simulate an aircraft flyover as a sequence of source positions[2,20]. Aircraft auralization models allow the receiver to move around, while the propagation path is recalculated for each individual position[2,20]. In contrast to urban acoustic models, in aircraft auralization models, it is possible to calculate the impact of meteorological factors on the propagation path with a higher level of precision. Arntzen and Simons developed a framework to adjust the propagation path to weather conditions, using a ray-tracing algorithm and only considering direct paths and ground reflections[2,15]. Arntzen and Simons's method embeds a novel approach to calculate the effects of atmospheric refraction [15]. As the air comprises various inhomogeneous layers with different wind and temperature variables[2,21,22], their model adjusts the propagation path based on the refraction level per layer[2]. The combination of the sound power level, the source directivity and the propagation path determine the sound level experienced by the receiver. Although ground reflections are calculated in the model by Arntzen and Simons, a comparison between their model and measurements showed that the model overestimates the effects of wave interference[15]. Heuristic urban acoustic models use a comparable, yet simplified, approach to simulate atmospheric refraction. Models such as Harmonoise and Nord2000 change either the curvature of the propagation paths or the ground surface to calculate refraction[23,24]. In both cases, the curvature is based on a logarithmic increase of the wind speed, a linear increase of the temperature by height, and the roughness of the ground[24,25]. However, as the models only attribute one linear speed of sound gradient for the entire atmosphere, the models compute a (single) linear approximation of the logarithmic pattern [23,24]. Alternatively, a standardized linear speed of sound gradient can be attributed to the atmosphere, based on weather classifications[21].

6.3.2. Testing a hybrid method

This study evaluates an intermediate simulation approach between the aircraft auralization framework by Arntzen and Simons[15], and the methods used to simulate aircraft noise around buildings by Ismail and Oldham[11] and Hao and Kang[9]. As in these previous studies, an urban acoustic model based on ray-tracing and image source algorithms was used. The urban acoustic model in this study also applies the same ground impedance method as was used in the auralization study. Instead of simulating an aircraft flyover as a line or single point source, the method in this study assumed an aircraft flyover as a sequence of positions, like the aircraft auralization model. However, as refraction is calculated in a relatively simplified way, i.e. a linear gradient for the whole atmosphere, compared to e.g. aircraft auralization models, the hybrid method in this study is evaluated by means of two experiments. The first experiment was modelled after the auralization study by Arntzen and Simons[15]. In the study by Arntzen en Simons, comparisons were drawn between the influence of a homogenous and a non-homogenous atmosphere on the sound level at the receiver's location. As urban acoustic models use a simplified approach to correct for atmospheric effects, the first objective was to identify the differences between both models. Thus, the intermediate approach, as presented in this study, was compared to Arntzen and Simons' results. Secondly, as Arntzen and Simon's model excludes spatial geometries, the influence of atmospheric refraction on aircraft noise in scenarios containing vertical walls was analysed. A secondary objective of this study was to define a sensible upper limit for the maximum diffraction rate around buildings. Although a higher diffraction rate increases the accuracy, it also makes the model significantly slower. To test the applicability of the method for real cases, i.e. for buildings at a substantial distance from a flight path, a second experiment compared the numerical sound levels around buildings with in-situ measurements. Hence, the study used the same locations and data as in chapter 5. Measurements carried out at three locations near Amsterdam Airport Schiphol (AAS from now on) were used as benchmark cases. The study only considered the results of take-offs from one runway, all of which were ascending in a straight direction. In the second experiment, the sound levels around buildings were calculated for different refraction gradients, and then they were compared to the measurements and each other.

6.3.3. Refraction and edge diffraction around barriers

For the first experiment, flight paths were simulated as a sequence of static spherically radiating monopoles with a wideband spectrum over a straight length of 12000 meters (from x=6000m to x = -6000m), positioned at intervals of 200 meters, and 500ft (152m) above the ground surface. The source power level was set at 150dB for all 1/3-octave-bands between 50Hz and 10000Hz. The source power was based on literature[2], but had no direct impact on the results, as the study only focused on the insertion loss per frequency. The insertion loss only considers the effect of the propagation path between the source and the receiver. Hence, the insertion loss is independent from the sound power level. The position of the receiver was 1.7m above the ground, halfway the flight track (x = 0m), at a lateral distance of 50m from the ground track of the aircraft flyover.

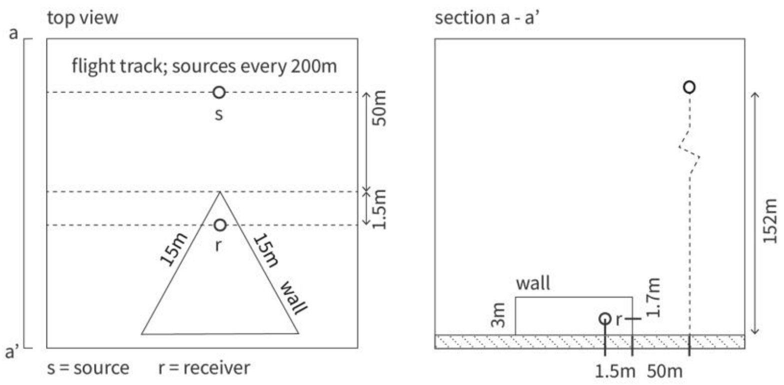

Figure 43 Top view and section of the model set-up for experiment 1; s(n) and r are positioned at x = 0m

The reference study showed that path curvature only had an effect when the angle at which the eigenray reaches the receiver is sufficiently small (i.e. <15 degrees). In ray-tracing, a large number of rays is launched to explore the possible paths between the source and the receiver. The eigenray is the (direct) path that reaches the receiver and is often the only (direct) path processed. To verify this conclusion for a situation including vertical obstacles, three identical walls forming an equilateral triangle (3m high and 15m wide) were placed around the position of the receiver in the simulation (see Figure 43). The walls' material was set as 'hard surfaces', while the properties of the ground surface were comparable to those in the reference study[15] (i.e. 'dirt road' in Table 6).

Table 6 Effective flow resistivity of (ground) surface materials in this study.

Material	Effective flow resistivity (kPa/m2·s)
Water	30.000
Hard surfaces	20.000
Dirt, road side	800
Pasture	205
Grass / pasture	205
Earth / soil, sparse grass	100
Forest floor	40

As the urban acoustic model differs from the initial auralization model, the method as tested in this study had a few limitations. Firstly, the study focuses on time instances instead of a moving source and receiver. In the initial experiment, the source moved at a speed of 100m/s while the receiver moved perpendicular to the flight path at a speed of 1.4m/s. Therefore, the location of the receiver was moved stepwise 2.7m away from the flight path for each source position. However, to compare the effects of atmospheric refraction when walls are placed around the receiver, the position of the receiver and walls was kept constant (i.e. 50m away from the flight path). Secondly, for the synthesis of the sound signal, Doppler corrections were applied to the tones, which are dependent on the position and speed of the source. To avoid a similar Doppler correction in this study, it only considers the insertion loss per frequency. The insertion loss reported in the references study was also compared with the results in this study. Results were analysed per 1/3-octave band for frequencies between 63Hz and 1000Hz; these analyses are introduced in more detail in section 6.3.7.

6.3.4. Simulations compared to measurements

In the second experiment, the results of the numerical calculations were compared with in-situ measurements. Hence, the three buildings at the case locations (A, B and C, as introduced in the previous chapter) were used. The buildings and microphones considered in the experiment were A1-A2, B3-B4 and C4-C5, see Figure 27 in chapter 5. Only the results for straight flight paths with a time domain of 60s around the aggregated L_{Amax} values, were used for this study (see chapter 5). The experiment was structured in a similar way to the first experiment, i.e. the study focused on the effects a refracting and a non-refracting atmosphere had on the results. Therefore, three calculation approaches were compared:

1. No curvature, which was used in previous studies[9,11,12].
2. Path curvature with a (single) linear speed of sound gradients varying between $0.002s^{-1}$ and $0.010s^{-1}$ with and interval of $0.002s^{-1}$.
3. Path curvature based on the Nord2000 lin-log approximation method, with the meteorological input data described in Table 2 in chapter 5.

As in chapter 5, the relative attenuation around buildings ΔL_{eq} was considered, which eliminates the role of individual differences between aircraft flyovers caused by things like aircraft and/or engine type and thrust. Moreover, this also smooths over any variations between aircraft flyovers that are induced by local atmospheric fluctuations, which can result in e.g. spectral broadening and wind eddies[15,21]. Results for each of the curvature gradients were compared to each other and benchmarked against the results of the aggregated measurements.

Aircraft flyovers were modelled as static monopoles at the mean aircraft positions from the aggregated data on a time interval of 3s (see Figure 29 in chapter 5). The same source power settings as those for the first experiment were used. The source positions were located with the built-in Geo-location tool in SketchUp2017[26].

6.3.5. Simulation model

In this study, a commercial model (OTL suite) based on a ray-tracing and image source algorithm was used. Engineering models usually implement ISO-9613[27], which sets the standards to calculate the propagation of sound in outdoor environments. In contrast, OTL combines a ray-tracing basis with solving Helmholtz wave equations to calculate the sound propagation. Therefore, the package could be seen as an intermediate between traditional engineering and (full) wave-based acoustic models[28]. The model has a higher level of fidelity than ISO-9613, but keeps the calculation time reasonable[28,29]. The model considers the propagation paths in a three-dimensional space, which makes the model interesting for aircraft noise, which is more difficult to approach as a two-dimensional problem, as the position of the source changes in all three directions (x,y,z).

The model implements a range of calculation methods, based on publications and previous research. The basis, formed by a ray-tracing engine[30] and image-source relevant path detection[31], is combined with diffraction[32,33] and reflection[34] coefficients for spherical waves. Surface properties are based on material impedance[35], while the model applies empirical standards for atmospheric attenuation[36] and turbulence[23,25,37]. Atmospheric refraction, simulated as ray curvature, is based on the Nord2000 method. The sound speed gradient can be set either as linear or as a linear approximation of a logarithmic profile, with the temperature, roughness constant, wind velocity and wind direction as the input parameters[38]. The model uses the following equation to calculate the sound pressure level at the position of the receiver ([28,29,39]):

$$p_{receiver} = \sum_{y=1}^{q} \sum_{n=1}^{n} p_y \frac{e^{jkR_i}}{R_i} \prod_{0=1}^{x} c_0 \qquad (6.1)$$

In this equation q refers to the number of sound sources, n refers to number of sound paths arriving at the receiver, p_y stands for the power level of the source(s), $\frac{e^{jkR_i}}{R_i}$ describes atmospheric attenuating due to spherical radiation, and $\prod_{0=1}^{x} c_0$ represents the coefficients describing diffraction, refraction and turbulence of the transmission path between the source and the receiver.

6.3.6. Model settings

To reconstruct the locations in the models, buildings shapes and heights were based on data in the AHN[40] and TOP10NL. These databases contain open source GIS data with height and geometrical information on spatial objects in the Netherlands in DWG format[41]. SketchUp 2017 was used to simulate the case study sites, and shapes were exported to the acoustic model in DXF format. The basic shape of buildings and landscape elements, such as terrain elevations or cars, were included in the model. However, as recommended in the literature[16], small or permeable structures, such as trees and street furniture, were omitted to limit computational overhead. For the same reason, building ornaments and windows were omitted, and facades were made of generic ‘hard materials’ (see Table 6). For the ground surfaces, the materials were based on site observations and aerial pictures. In some cases, assumptions were made about the impedance of the surfaces, although these were not validated by in-situ tests. Table 6 shows the values for the effective flow resistivity of the materials used in the study, based on literature (see [35,42]). Building surfaces, asphalt and concrete ground surfaces were simulated as if made of 'hard' materials. For location B, additional ground patches, classed as 'pasture' and 'earth', were added on top of the overall ground surface. For location C, patches of 'forest floor', 'water' and 'grass' were added to the configuration. For the ground surface between the ground positions of both the flight track and 50m before the first buildings at a location, the material 'agricultural land' was used (see Table 6).

6.3.7. Analyses

6.3.7.1. Refraction and edge diffraction around barriers

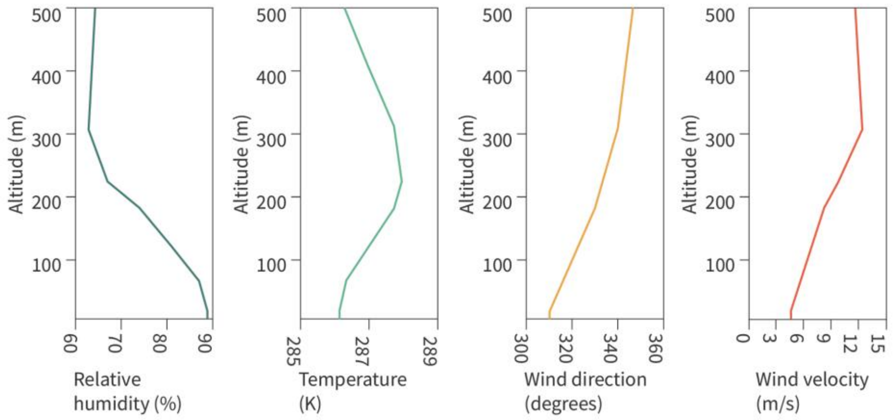

Figure 44 Weather data as used in the simulation, adapted from the reference study[15].

Table 7 Scenarios as simulated, refraction is calculated based on the Nord2000 log-lin approximation with input data from Figure 44.

Scenario	Walls	Refraction	Max. diffraction order
1	No	No	1
2	No	Yes	1
3	Yes	No	1
4	Yes	No	2
5	Yes	No	3
6	Yes	Yes	2

The first experiment focused on the maximum diffraction order and refraction. To determine the maximum diffraction order, the diffraction order per path was increased stepwise, by integers only. For each step, the results were compared to the data of the previous stage. The upper limit was set as the integer minus one for the value that did not induce a significant change compared to the previous integer. As the data is not normally distributed, a non-parametric Kruskal-Wallis test with Bonferroni post hoc corrections was used to compare the results between the steps.

To simulate a refracting atmosphere, ground weather data (as used in the reference study and shown in Figure 44) was used to calculate the Nord2000 log-lin approximation. The reference study calculated the total path curvature as the summation of refraction per air layer, whereas the Nord2000 log-lin approximation assigns one (linear) gradient for the atmosphere. The function assumes that the wind speed and temperature increase logarithmically. In the first experiment, six scenarios were considered (see Table 7 for the characteristics of the scenarios). Results were studied by means of the insertion loss (IL) and L_{eq}, and then plotted per position, for 1/3-OBs between 63Hz and 1000Hz. The L_{eq} was calculated based on the following equation:

$$L_{eq} = 10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_p(t)}{10}} d(t)\,\Delta_{ni}\right) \tag{6.2}$$

The time length n refers to the time, in this case the total number of positions, and $L_p(t)$ to the sound level (in dB) per position.

6.3.7.2. Simulations compared to measurements

In the second part of the experiment, three approaches to calculate aircraft noise around buildings were compared with each other. Additionally, the calculations were benchmarked against the aggregated results of in-situ measurements for take-offs near a runway. Here, the mean sound pressure levels and flight positions were calculated based on the data in chapter 5. The time interval between positions and sound pressure levels was kept at 3s, due to the resolution of the ADSB data. The aggregated mean sound pressure level per position was based on the following equation:

$$L_{(t)} = 20log\left(\frac{\frac{1}{n}\sum_{i=1}^{n} p_t}{p_0}\right) \tag{6.3}$$

In which $L_{(t)}$ refers to the sound level in dB at a position t given in seconds. The p_t refers to the sound pressure level in Pa for a position *t*, and p_0 refers to the reference sound pressure ($2\cdot10^{-5}$Pa). In this study, the results for the mean aggregated paths, i.e. one per location, were used for analysis in terms of the L_{max} and L_{eq}. To make both factors independent of source variations, such as the aircraft type and engine class, the relative difference between two points around a single building was calculated. In other words, the relative difference between the sound levels was measured near a building side facing towards a flight paths (*d*LOS side), and the opposite facade facing away from the flight path (*n*LOS side) (for more details, see chapter 5). Three metrics were analysed: the ΔL_{max}, ΔL_{eq} and the time variance of ΔL_{eq}. Here, the ΔL_{max} is the maximum sound attenuation around a building during an aircraft flyover. The ΔL_{eq} is the average sound attenuation between two facades during an aircraft flyover. Congruence between the calculated and measured ΔL_{max} values may hide a skewed distribution of energy, resulting in deviating values between measured and calculated ΔL_{eq}. Therefore, the ΔL_{eq} and time variance of ΔL_{eq} were used to analyse both the calculated and measured values for the sound level and the time lapse. Results were analysed per 1/3-octave band for frequencies between 63Hz and 1000Hz. Non-parametric Kurskal-Wallis and Bonferroni post-hoc tests were used to compare the calculation methods.

6.4. Results

6.4.1. Refraction and edge diffraction around barriers

6.4.1.1. Without walls

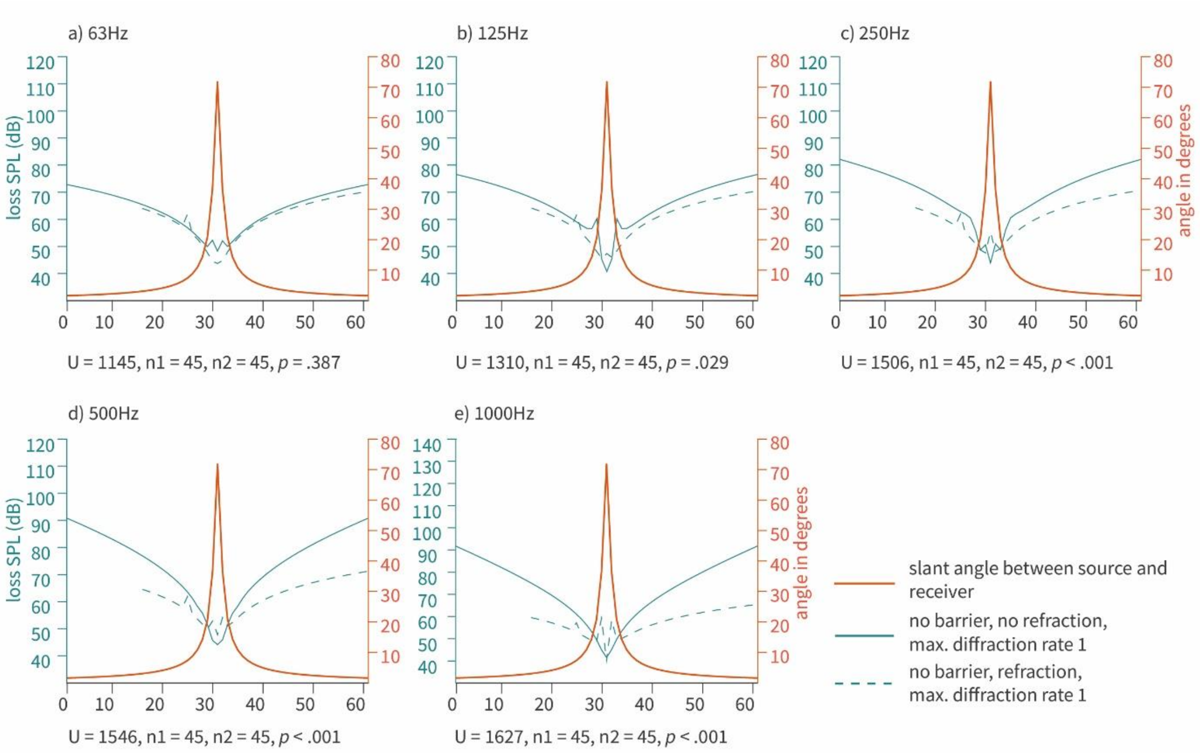

Figure 45 Results for two scenarios (refraction / no refraction) when there are no walls around the receiver. Results from the Mann-Whitney-U test are given below each figure (results are given in 1/3-octave bands, centre frequencies).

Table 8 L_{eq} per scenario and per 1/3-octave band in dB (centre frequencies).

Frequency	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
63Hz	67.5	64.3	81.3	71.6	71.4	74.9
125Hz	70.8	64.4	84.0	73.4	73.5	80.4
250Hz	75.8	64.7	95.8	84.4	83.4	87.4
500Hz	83.2	65.1	109.5	96.4	95.6	92.0
1000Hz	94.0	65.6	122.2	108.5	108.2	104.1

Table 9 Minimum IL per scenario and per 1/3-octave band in dB.

Frequency	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
63Hz	48.1	43.6	55.3	40.3	37.4	50.8
125Hz	40.6	45.4	57.1	38.9	37.8	50.5
250Hz	43.8	47.4	61.4	45.5	44.1	51.1
500Hz	44.0	47.6	57.4	46.2	45.3	52.7
1000Hz	43.3	41.7	58.7	47.9	47.7	55.9

Figure 45 shows the results of the first experiment as plotted per 1/3-octave band. The figures show the reduction of the sound pressure level on the imaginary flight path per position (60 in total). The figures show clear differences between the frequencies, and between the results calculated with and without refraction. The latter is manifested when the slant angle is small (<15 degrees) and increases with frequency. For the scenario with refraction, the absence of results during the first 16 positions can be attributed to a shadow zone, a side-effect of upwind refraction in ray-tracing models. This means that the microphone is positioned beyond the upper limit of an upwind refracting path, hence no rays reach the microphone. Table 8 and Table 9 give the minimum insertion loss (IL) and L_{eq} values for the different scenarios. Although the minimum IL values are comparable for most frequencies, there are clear differences between the two scenarios in terms of the L_{eq}. However, results from the non-parametric Witney-Mann U test show that results were not significantly different, except for the 1000Hz 1/3-OB. Figure 45 suggests that the results are also significantly different for the 500Hz 1/3-OB. Although this is not supported by the results of the statistical tests, it should be taken into account that the size of the data set might is relatively small.

6.4.1.2. *With walls*

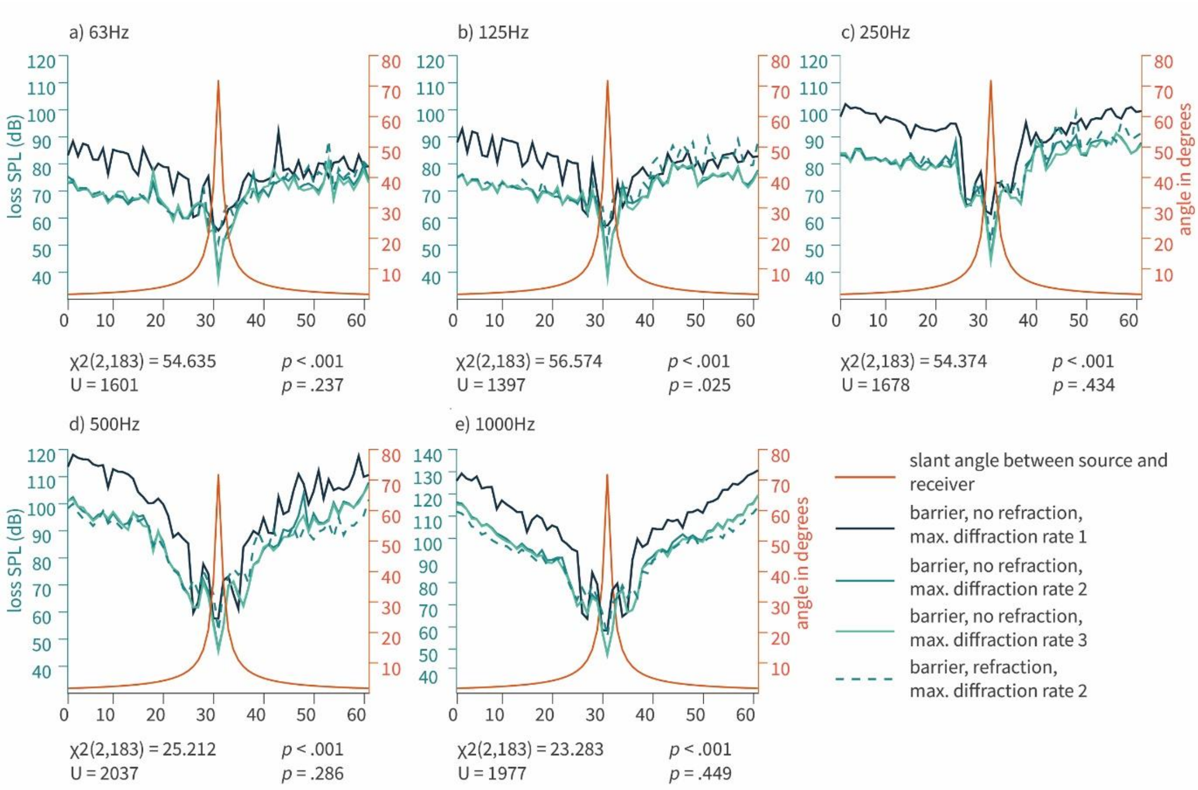

Figure 46 Results for scenarios with walls around the receiver and increasing values for the maximum diffraction rate, and for a case with and without path curvature. Results from the Mann-Whitney-U and Kruskal-Wallis tests are given below each figure (results are given in 1/3-octave bands, centre frequencies).

Table 10 Results of Bonferroni post hoc tests to determine the maximum diffraction rate, only significant results are given.

	63Hz	125Hz	250Hz	500Hz	1000Hz
1-2	<.001	<.001	<.001	<.001	.001
1-3	<.001	<.001	<.001	<.001	.001
2-3	-	-	-	-	-

In the second part of the experiment, walls were placed around the receiver. Figure 46 shows the results per 1/3-octave band for calculations with varying maximum diffraction rates. Results were studied with a Kruskal-Wallis test to define a sensible maximum diffraction rate. Consequently, a Mann-Witney U test was used to compare the effects of a scenario with and without refraction. Based on the results of the Kruskal-Wallis and Bonferroni post hoc tests, it was decided to keep the maximum diffraction rate at 3 (see subscripts Figure 46). The Bonferroni post hoc tests revealed a significant difference between a maximum diffraction rate of 1 versus 2 and 3, but not between a maximum diffraction rate of 2 and 3 (Table 10). If walls are present, the Mann-Witney U tests showed no significant difference between scenarios with and without refraction, although Table 9 shows that differences in terms of ΔL_{min} can be large (>5dB). Even though the L_{eq} values can be comparable, the

ΔL_{min} values show that the level of shielding behind a wall is smaller in the case of a refracting atmosphere.

6.4.2. Simulations compared to measurements

6.4.2.1. ΔL_{max} and ΔL_{eq}

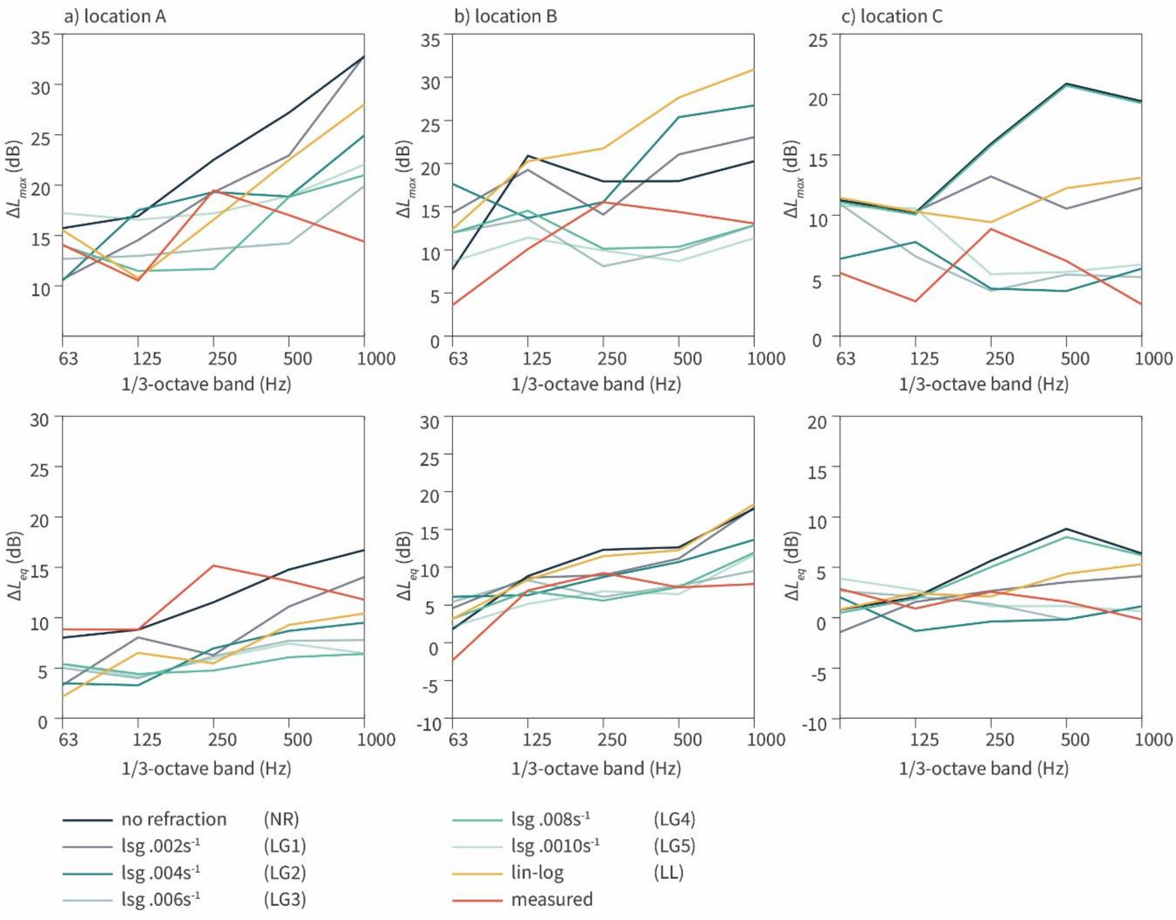

Figure 47 Results for ΔL_{max} and ΔL_{eq} (centre frequencies 1/3-octave bands) per calculation method and measurements.

Table 11 Results from Kruskil-Wallis tests for the data in 1/3-octave-bands between 63Hz and 1000Hz (centre frequencies), comparing the difference between calculation methods.

	63Hz	125Hz	250Hz	500Hz	1000Hz
A	$X^2(6,140) = 12.120$ $p = 0.059$	$X^2(6,140) = 18.595$ $p = 0.005$	$X^2(6,140) = 7.510$ $p = 0.276$	$X^2(6,140) = 29.431$ $p < 0.001$	$X^2(6,140) = 33.908$ $p < 0.001$
B	$X^2(6,140) = 19.939$ $p = 0.003$	$X^2(6,140) = 3.718$ $p = .715$	$X^2(6,140) = 29.809$ $p < 0.001$	$X^2(6,140) = 34.984$ $p < 0.001$	$X^2(6,140) = 57.979$ $p < 0.001$
C	$X^2(6,140) = 10.654$ $p = 0.100$	$X^2(6,140) = 21.666$ $p = .173$	$X^2(6,140) = 25.657$ $p < 0.001$	$X^2(6,140) = 70.753$ $p < 0.001$	$X^2(6,140) = 61.128$ $p < 0.001$

In the second experiment, the effect of path curvature (refraction) was compared with the aggregated measurements. The study focused on the relative difference between two microphones, each at different sides of a building or street. The results were studied for three locations (A, B and C), and for 1/3-OBs between 63Hz and 1000Hz. Figure 47 shows the maximum difference (ΔL_{max}) for each simulation approach, and for the measurements. To analyse the difference between the simulation approaches, a series of Kruskal-Wallis and Bonferroni post hoc tests were carried out (see Table 11 and Table 12). Figure 47, Table 11 and Table 12 show a division between the results for (linear) gradients <0.004s^{-1} and the results for linear gradients >0.006s^{-1}, for 1/3-OB >250Hz. By comparison, the results from the second group fit better with the measurements than those from the first group. The results for simulation approaches that used small linear gradients (<0.004s^{-1}), or used the lin-log approximation or that were without refraction overestimate the sound attenuation, especially for higher frequencies (i.e. >500Hz). For example, while the maximum difference between the measurements and the calculations is approximately 6dB for a linear gradient of 0.006s^{-1}, the difference exceeds 13dB for straight paths (no refraction). Figure 47 (L_{Amax} graphs) and Table 12 suggest that refraction can be omitted for frequencies <250Hz, with results closer to the measurements for the simulations without refraction, as the alternative methods (with refraction) seem to underestimate the shielding effect of the buildings. However, this effect is also present for the 250Hz 1/3-OB, which was somewhat unexpected. Nevertheless, the overall results of the simulations with linear gradients between 0.004 s^{-1} and 0.008 s^{-1} are more congruent with the measurements compared to the results of simulations without refraction, or calculations based on the lin-log approximation. The L_{eq} graphs show that the calculations based on a refracting atmosphere are closer to the measurements for location B and C, which is the opposite for location A. Therefore, to study the distribution and variation of sound energy during the flyovers, the time variance was studied.

Table 12 Results from Bonferroni post-hoc tests for the data in 1/3-octave-bands (centre frequencies) between 63Hz and 1000Hz.

Calculation methods	63Hz			125Hz			250Hz			500Hz			1000Hz		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
NR vs LG1	<.005									.004		.003	<.001		
NR vs LG2	<.008	<.001		0.005		.034			<.001	<.001		<.001	<.001	.002	.001
NR vs LG3	<.011	.006		<.001				<.001		<.001	<.001	<.001	<.001	<.001	<.001
NR vs LG4	<.010			<.001				<.001		<.001	.001		<.001	<.001	
NR vs LG5	<.004			.002				<.001		<.001	<.001	<.001	<.001	<.001	<.001
NR vs Lin-log	<.019			.005						.002					
LG1 vs LG2												<.001		.020	
LG1 vs LG3								.006			.002	<.001		<.001	
LG1 vs LG4								.012		0.033	.012			<.001	.001
LG1 vs LG5						.013					.001			.001	.002
LG2 vs LG4		.005		.020		.006			<.001			<.001			.002
LG2 vs LG5		.003		,014		<.001									
LG2 vs Lin-log		.016													
LG3 vs LG4		.025							0.012			<.001			<.001
LG3 vs LG5		.015				.002									
LG4 vs LG5									0.019			.001			<.001
Lin log vs LG2						.005			<.001		.009	<.001		.002	<.001
Lin log vs LG3								.001	0.049		.001	<.001	.009	<.001	<.001
Lin log vs LG4								.001			.005		.023	<.001	
Lin log vs LG5								.007	0.011		<.001	.005		<.001	<.001

6.4.2.2. Time variance

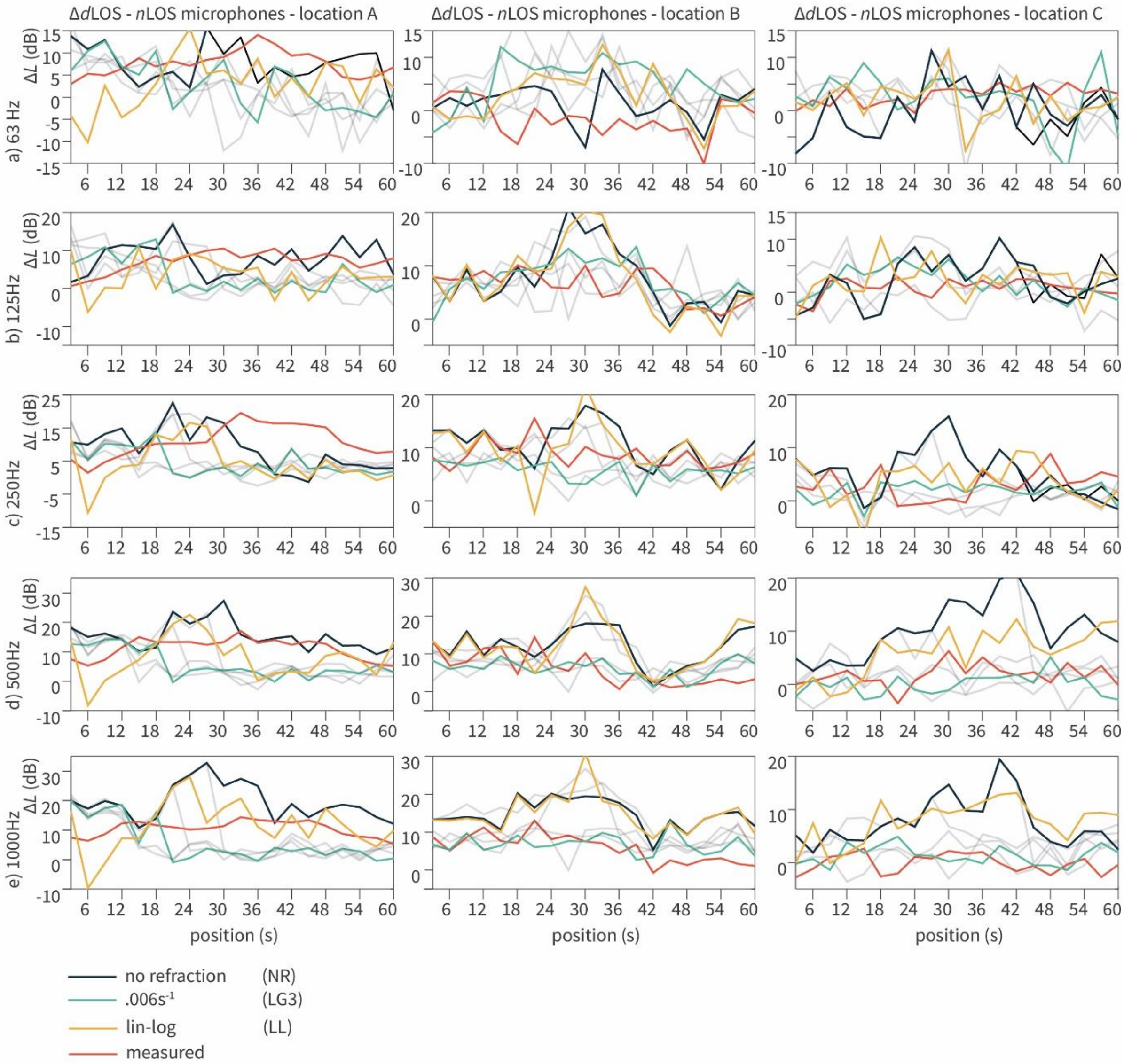

Figure 48 Difference between microphones per 1/3-OB (centre frequencies ΔL), plotted per position in time (in s), for location A, B and C.

Figure 48 shows the time variance of ΔL for the 20 positions analysed (i.e. one position per 3s). Because the results for a linear speed of sound gradient of $0.006s^{-1}$ were closest to the measurements in terms of ΔL_{max} and ΔL_{eq}, only this linear value was considered for further analysis. The time variance plots give more detail on the congruence between the measurements and the simulation approaches.

Firstly, Figure 48 shows that, for most cases, the ΔL increases to a peak level before decreasing to the initial level. The maximum ΔL varies between the different calculation methods and is, for most frequencies and locations, greater for speed of sound gradients $<0.004s^{-1}$ than for higher gradients.

Secondly, the position of the maximum ΔL (in time) varies for the three calculation methods and is skewed compared to the physical observations. Compared to the measurements, the noise reduction around buildings decays sooner for speed of sound gradients >0.004s^{-1}. Figure 48 shows that this effect is more pronounced for location A than it is for location B or C. As the horizontal and vertical distance between the source and the receiver increases, the greater the angle at which the rays hit the buildings. This means a steeper slope of the rays, thus reducing the abating potential of buildings. When the rays are also curved, the decay of the noise abatement by buildings will be even more rapid, as the curvature increases the ray angle even more. Compared to the measurements, Figure 7 shows that a linear speed of sound gradient underestimates the noise abating potential of buildings. However, this is different for the 63Hz 1/3-OB for location B, where all calculation methods overestimated the noise reduction around the buildings compared to the measurements. Figure 37 shows that the sound levels are similar around the building surrounded by microphones B-3 and B-4, and much lower at microphone B-3 compared to microphones B-1 and B-5. The main difference between these three *d*LOS microphones is the shape of the surrounding building. The effect might relate to the shape of the building inset in which microphone B-3 was placed, and the directivity of the sound. As the lower frequencies are attributed to jet noise, which emerges behind the engines, the low frequency 'rumble' will follow in the slipstream of the flyover. In other words, the aircraft will be far beyond an orthogonal position in relation to the building by the time the low frequency component of the spectrum is emitted. The direction of the sound wave will hit the building from aside, and here the building flanks coming into play, shielding the microphone from direct exposure to the sound. This effect can be seen in Figure 37 as well. The results for linear speed of sound gradients also decay too soon compared to the measurements. Hence, the distribution of the sound energy is skewed, which explains the good match between the results of simulation runs without refraction and the measurements in Figure 47a (for the L_{eq}).

Thirdly, for location A, the lin-log method shows a clear dip at 6s, due to a shadow zone caused by upwind refracting rays. Although not visible in the figures for the positions prior to 6s, an analysis of the paths in the model showed that these positions also lay in an upwind shadow zone. Because reflections near the *n*LOS microphone, i.e. the microphone near the building side facing away from the flight path, are weaker, the overall ΔL is still positive, which means that the sound level at the *d*LOS microphone, i.e. the microphone near the building side facing towards the flight path, remains higher than at the corresponding *n*LOS position. After 15s, the atmospheric situation turns to downwind refraction, with the location situated behind the source.

6.5. Discussion

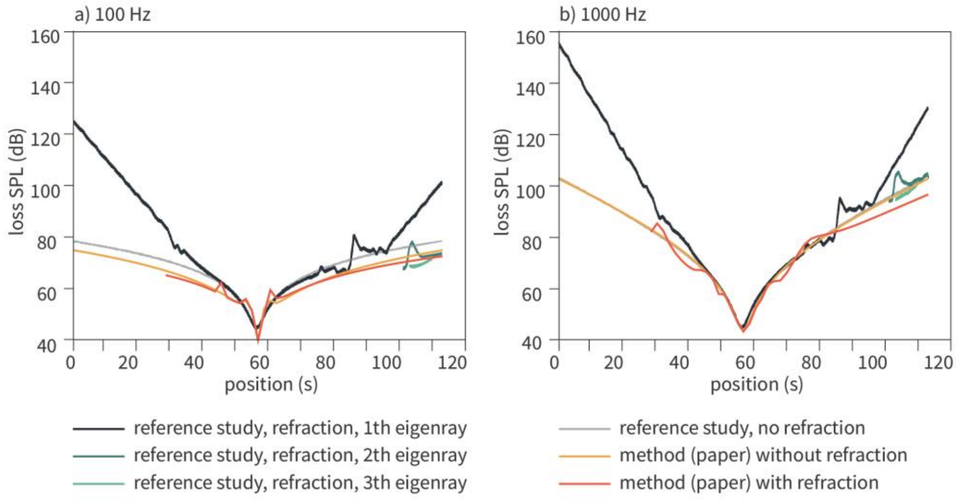

Figure 49 Comparison between the numerical results for a refracting and non-refracting atmosphere in the reference study and the first experiment for a) 100Hz and b) 1000Hz.

The results of the first experiment were compared with the study by Arntzen and Simons[15]. Figure 49 shows the results for the insertion loss, plotted for 100Hz and 1000Hz. Based on the comparison, three observations can be made. Firstly, the sound pressure levels in the urban acoustic model are seemingly higher for 100Hz. The figures show that Arntzen and Simons[15] only considered the contribution of the eigenrays. This means that ground reflections were not included, unless the eigenray is a second or third order ground reflection. For 100Hz, Figure 49a shows that the contribution of ground reflections reduce the insertion loss. To analyse the contribution of the ground reflections in the urban acoustic models, calculations were repeated for the four positions, i.e. 1s, 20s, 100s and 117s. The results showed that the insertion loss was between 2dB and 3dB higher, which conforms to the results in the reference study. The ground reflection also induced the small peaks mirrored on both sides of the minimum insertion loss. The graphs show that the contribution of the ground reflection is weaker for 1000Hz. Secondly, the models agree in terms of refraction. However, the graphs in the reference study are less constant and more volatile, due to the volatility of atmospheric effects. As the propagation path is the summation of small segments, local weather variations can change the direction of individual segments. Thirdly, Arntzen and Simons applied a correction for the upwind-related shadow zone, hence their graphs calculated results for the receiver positions in the shadow zone (<30s).

Regarding the second experiment, another three observations can be made. Firstly, the results indicate that, if refraction was neglected, the model overestimated the sound attenuation around buildings. Secondly, the results based on the lin-log approximation were not significantly different from the scenarios without refraction. This was a somewhat surprising conclusion, as the expectation was that the lin-log approximation would yield a more representative gradient than the other options. Comparing the numerical results and the measurements, this conclusion applies for all frequencies, although the effects are stronger for the 500Hz and 1000Hz 1/3-OBs. However, caution is needed for the interpretation of these results, as the ambient sound levels sets an absolute lower limit. Although buildings may attenuate the sound levels substantially for these frequencies, it is difficult to measure the exact attenuation in-situ. Thirdly, linear speed of sound gradients >0.006s^{-1} reduced the gap between measurements and calculations. The results were significantly different from the other options, i.e. scenarios without refraction or with refraction based on the lin-log approximation. However, this only applies for the 1/3-OBs >125Hz for location B and C. The statistical test revealed that the linear speed of sound gradients between >0.006s^{-1} and <0.010s^{-1} was significantly different for 1/3-OBs >250Hz, especially for location C. However, a linear gradient of 0.006s^{-1} showed results closest to the measurements for all three locations, although that the differences between simulations were smaller for 1/3-OBs <250Hz. Measurements were carried out during summer, near one runway, and only focused on take-offs. Hence, variations in temperature, wind speed and wind direction were minimal, which could explain this result. For example, the wind velocity ranged between 4 and 5Bft. More research is needed to study the difference between speed of sound gradients for different weather profiles. Another limitation of the current study is the omission of smaller facade ornaments, such as ledges, window frames, and materials variations of the building surface, but also trees and landscape artefacts, which was needed to increase the calculation speed of the acoustic model. Although the authors expect that it is legitimate to discard such level of detail for the buildings at location B and C, this might be different for the building at location A, which has more protrusions and surface irregularities. More research is needed to study the importance of such details in relation to the computational model. Likely, such details will become more important for smaller wavelengths, and particularly affect mid and higher frequencies. This could partially explain the increasing difference between the results from the measurements and simulations, which become bigger for higher frequencies. However, this observed difference can also be attributed to the difficulty to measure the full abatement of aircraft noise by buildings for the higher frequencies due to atmospheric absorption and the masking effect of the ambient sounds. In other words, even if the sound attenuating potential of buildings is as large as the simulations predict, it is incredibly difficult to test this by means of in-situ measurements. Finally, the ray-tracing character and the settings of the model also influences the results. To keep the calculation time acceptable, the maximum number of reflections and diffracted reflections is capped, which means the model considers a finite number of paths. Another point of attention is the way the model deals with atmospheric refraction, namely, by means of (linearized) curved rays. This means that, in some cases, a small change of e.g. the source or receiver positions, or the building configuration, could mean that the curved ray suddenly, or (the opposite) no longer, reaches a receiver. In that case, the sound level is defined either by reflected and diffracted paths, or directly exposed to the curved (first order) eigenray. In the results, this binary effect is manifested by sudden jumps, e.g. from a situation without any shielding provided by a building to a situation in which a building casts a decent noise shadow. This is a typical side-effect of ray-tracing model and could be solved by using full wave-based, or potentially radiosity, models instead.

For low-flying aircraft flyovers, or for receivers located near the ground track of the flyover, the atmosphere can be assumed to be homogenous and non-refracting. In respect to the studies by Hoa and Kang[9] and by Ismail and Oldham[11], a refracting atmosphere would not have changed their results or conclusions. Hoa and Kang[9] considered the effect of an aircraft flyover at 400ft (≈123m) and with a maximum distance of 1000m between the ground track and the first row of buildings. With a velocity of 100m/s, this corresponds to a time window of +/-10s around the position (in time) of the minimum insertion loss in Figure 49. The figure shows that within this window, the results for path with and without refraction are similar. Ismail and Oldham[11] considered an aircraft flyover at 60m above the street. This corresponds to an even smaller time window around the position of the minimum insertion loss in Figure 49.

6.6. Conclusions

This paper evaluated the use of an urban acoustic model to predict the propagation of aircraft noise around buildings which were located at a substantial distance from a flight path. The study had the following three objectives:

1. To develop and test an intermediate approach between an aircraft auralization and an urban acoustic numerical model.
2. To define the importance and influence of atmospheric refraction for the prediction of aircraft noise dispersion around buildings.
3. To analyse the difference between a simplified method to calculate atmospheric refraction in an urban acoustic model and in-situ measurements.

In the first part of the paper, the results of the intermediate approach were compared with a reference study, for a homogenous and refracting atmosphere. In the reference study, an aircraft fly-over was simulated as a series of source positions, while refraction was the summation of the speed of sound gradients of the different atmospheric layers. The study was repeated in an urban acoustic model, in which refraction is based on a single gradient. As in the reference study, the results from the urban acoustic model showed minor differences between a refracting and non-refracting atmosphere. Visual inspection of the results showed that the results and graphs are very similar when the slant angle between the aircraft and the receiver is >15 degrees. For a refracting atmosphere, the results between both studies slightly deviate, although the differences are relatively small. When walls were placed around the receiver, there is a wider variation in the results as calculated for individual source positions. This can be attributed to a constantly changing angle of incidence and specular reflections between the walls.

In the second part of the paper, the method was used to compare calculations and measurements for three case study locations. Instead of low-flying aircraft, the study considered locations at a substantial distance from the flight paths, for take-offs with an altitude between 350m and 1100m. Again, the study focused on the difference between results for a homogenous and refracting atmosphere. For the latter, alongside the Nord2000 lin-log approximation, the calculations were repeated for five linear gradients between $0.002s^{-1}$ and $0.010s^{-1}$, on an interval of $0.002s^{-1}$. The results of the different calculation methods were compared to each other and benchmarked against measurements. The results showed no significant differences between a homogenous and refracting atmosphere, when the speed of sound gradient was based on the Nord2000 lin-log approximation. Compared to the results of the measurements, results for both methods overestimated the noise reduction around buildings. Instead, for 1/3-OB >250Hz, the results for linear speed of sound gradients $>0.004s^{-1}$ showed a significant difference when compared to the calculations without refraction. For the location closest to the flight track, the results were clearly different for all frequencies between 63Hz and 1000Hz. Additionally, the results for linear gradients $>0.004s^{-1}$ fit better with the measurements. However, for large values, the noise abatement around buildings can be underestimated and decays too quickly in comparison with the measurements.

To conclude, the intermediate, yet simplified, method presented in this study demonstrates good agreement with the reference study. Refraction can be neglected if the receiver is located close to flight path, and/or if the altitude of the aircraft flyover is relatively low. In other cases, i.e. for locations at a greater distance from a flight track, refraction should be included. To simulate refraction based on a single speed of sound gradient, the results of linear speed of sound gradients $>0.004s^{-1}$ and $<0.010s^{-1}$ were closest to the measurements for all three locations. In respect to the calculation of the peak exposure levels, the maximum differences between the numerical approach and measurements were about 6dB for incident 1/3-octave bands for the best method (linear speed of sound gradient of $0.006s^{-1}$), but are below 3dB in most cases. This result was also found for the ΔL_{eq}, except for location A, where the noise reducing effect is underestimated by the model in relation to the position of the aircraft, which skews the distribution of the sound energy in the graph. The method described in this study can be used to estimate the sound attenuation of aircraft noise around buildings. However, more research is needed to study variances between different speed of sound gradients and weather variations, but also on the relevance of building details and ornaments.

6.7. Literature

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7. The potential of architectural and urban design to reduce aircraft take-off noise at three sites near a flight path

7.1. Abstract

Buildings can reduce the exposure to aircraft noise when it is local. However, it is unclear how individual architectural design variables contribute to the attenuation of aircraft noise. This paper presents the results of a study in which the noise abating effects of such variables was studied in three case study areas. The areas are all located near the same flight path, but with varying horizontal and vertical distances between them and the aircraft. To compare the sets of results across the three locations, a similar baseline scenario was used in the simulations for all three locations, with varying street canyon widths. The following design variables were studied: 1) building height, 2) facade orientation, 3) roofs and loggias, 4) surface materials and 5) the orientation of the street. A numerical acoustic model was used, with the weather conditions corresponding to those of a typical summer day in Northwest Europe. The results showed that the noise reduction was significantly higher if the building height was increased, or if overhanging roofs and loggias were added to the baseline scenarios. To abate noise at a wide spectrum, wider streets canyons yielded better results. It was estimated that sound levels near buildings sides which do not face towards the aircraft are between 5dB and 15dB lower (depending on the frequency), than levels near building sides that do.

7.2. Introduction

Areas near airports and flight paths are exposed to noise and air pollution from aircraft. Noise exposure can result in mental and physical stress which negatively impacts health and quality of life[1–3]. Over recent decades, governments, planners, aircraft manufacturers, airport authorities and scientists have joined forces to make aircraft quieter and reduce adverse noise exposure. ICAO's Guidance on the Balanced Approach to Aircraft Noise Management is the international standard for noise abatement around airports. It presents four levels at which aircraft noise can be reduced, one of which is land use planning and management[4,5]. Within this category, noise contours and acoustic insulation schemes are the most prevalent strategies[5]. Practically, this means that noise contours are drawn up, which then prohibit building activities that are too close to runways and flight paths[6,7].

Unlike for other traffic sources, buildings barely abate sound emanated by an aircraft flying perpendicularly or almost directly over a street[8–10]. On the contrary, depending on the surface material, reflections between facades can amplify the sound level within streets in some cases. But when areas are further away from a flight path, studies show that buildings can reduce the exposure to aircraft noise[11,12]. Hoa and Kang[11] compared the noise levels for twenty-five urban sites, increasing the distance stepwise between area and the flight path. The greatest horizontal distance that they measured between a site and a flight path was 1000m, while the maximum flight altitude was set at

400ft (122m)[11]. Krimm[12,13] showed that sound levels around a single building can vary, and depend on the structure and design of the facade. Both studies show that the design of buildings and their facade ornaments can be used to reduce the exposure to aircraft noise in outdoor areas. However, except for facade textures, the existing literature does not indicate to what extent individual building design variables contribute to the reduction of aircraft noise. Furthermore, the literature is not clear about the noise abating potential of building design variance for sites which are located at a greater (or lesser) distance from a flight path.

The number of studies on buildings and aircraft noise is strikingly small compared to the wealth of literature that explores the potential of building design to abate road traffic noise. Over recent decades, numerous studies have focused on the road(?) noise abating potential of roof shapes[14], building protrusions[15,16], street width-building height ratios[15,17] and surface cladding[15,18]. For example, smaller street width-building height ratios prevent sound escaping from the street canyon to adjacent canyons[15]. Depending on the surface cladding and smoothness of the facades, sound levels can swell or fade within the street canyon[15,19]. Roof tops, and their number of edges, reduce sound energy by increasing edge diffraction, acting as acoustic wave breakers[20]. Saw-tooth shaped roofs, or roof edges with wall greening, are examples of effective design implementations to attenuate excess noise levels. The same goes for balconies and protruding elements within streets, which scatter and diffuse the sound field[12,15,16,21]. Balconies clad with porous materials on their parapets and ceilings also attenuate noise levels near facades[21]. In general, having vegetation and other similar forms of cladding on facades scatters and absorbs incident sound waves, which contributes to quieter streets and (adjacent) courtyards[18,22,23]. However, not every architectural intervention coined and tested in previous research can be used in a similar way for aircraft noise. A striking difference between aircraft and other traffic sources is the source directivity and the position of aircraft. Noise emitted by a source near the ground and surrounded by walls is confined to spread within a street. This means that road traffic noise cannot expand as freely as sound waves dispersed from overhead sources. Additionally, for aircraft noise, the distances between a source and a receiver are generally greater than for road traffic. This means that atmospheric refraction will play a more dominant role, such as influencing the angle at which sound waves hit a surface or obstacle.

This chapter presents the results of a study comparing the effectiveness of five architectural design variables at reducing aircraft noise around buildings. The study calculated the absolute and relative sound levels around buildings exposed to aircraft noise during a take-off. The effects of 1) building height, 2) facade orientation, 3) facade protrusion, 4) loggias and 5) green walls were considered for three locations near a flight path. In addition to the absolute sound reduction, the study also used numerical results to forecast the sound levels at the case study locations, relative to the ambient sound levels. The study had the following objectives:

1. To examine the aircraft noise abating potential of different architectural design variables for three canyon-width profiles.
2. To estimate the sound reduction induced by different architectural design variables at three sites near Amsterdam Airport Schiphol.

The chapter is divided in three parts. The first part introduces the research methodology, while the results are presented in the second part of the chapter. In the third part, the results are used to predict the sound levels around buildings for three locations close to Amsterdam airport. The chapter closes with the conclusions.

7.3. Methodology

7.3.1. Design of the experiment

Figure 50 Aerial images of locations A, B, C near a runway. The red shape marks the range in flight paths for aircraft taking off in a straight direction from the runway (image source: Google Maps). The yellow dots indicate the positions of the three microphones considered in this study, see chapter 5 for more detail.

As buildings influence the propagation of aircraft noise, the study calculated the sound levels around buildings with different architectural and urban designs. To ensure that the design alternatives were tested under the same conditions, a numerical acoustic model was used. The results were calculated for three locations, all at different distances from a flight path. The locations and the flight path were the same as those used in the previous chapters (see chapter 5 and 6 and Figure 50). The study only focused on straight flight paths, and results were based on the relative difference compared to a baseline scenario. As shown in Figure , the three locations vary in terms of urban form. To compare the results between locations, the existing urban form was neglected and replaced by an alternative urban configuration that acted as a baseline scenario, and was similar for all three locations (see section 7.3.4). The case study locations were also used to collect in-situ data, as presented in chapter 5. The final part of the study examined the noise levels for the case study locations, to predict to what extent the design interventions would change the current sound exposure levels, and the audibility of aircraft flyovers.

7.3.2. Simulating aircraft flyovers

The aircraft take-offs are simulated as a sequence of source positions with increasing height. The positions were similar to the source positions used previously in chapter 6. For each flight, the position of the aircraft was based on ADSB data and linked to the sound measurements based on time. In order to study the impact of buildings on the propagation of aircraft noise, the previous chapter aggregated the data of individual flights flying in a similar direction. Consequently, it was possible to compile a mean path (x,y,z) for each flight direction. In chapter 6, these results and positions were used as benchmark cases for the comparison of numerical simulation approaches. In this study, the same flight positions are used. Instead of changing the propagation path, here the urban areas exposed to aircraft noise are changed. As this study compared several architectural interventions against a baseline scenario, the results are independent from the sound power level of the source. Hence, in this study, the sound power level, source directivity and atmospheric refraction gradient were based on the conclusions of the previous study. This means that a single speed of sound gradient for atmospheric refraction of .006s^{-1} was used. The results for this gradient were closer to the measurements in comparison with the other simulations methods tested. In terms of the maximum differences, i.e. ΔL_{Amax} see chapter 6, between facades, the simulation approach showed differences below 3dB for most frequencies, and differences up to 6dB for incidental frequencies. A limitation of the model is that it underestimates the noise reducing potential of buildings exposed to aircraft noise, and assumes that the shielding effects decays too fast (especially for location A). Also, the model omits interference between sound waves, which is legitimate for most frequencies and building geometries, although wave interference might possibly increase or decrease the sound levels for lower frequencies in very specific cases (see chapter 6). In general, the numerical results were slightly conservative in respect to the measurements but deemed acceptable for the purpose of this study.

7.3.3. Numerical model[6]

In this study, a commercial model (OTL suite) based on a ray-tracing and image source algorithm was used. Engineering models usually implement ISO-9613[27], which sets the standards to calculate the propagation of sound in outdoor environments. In contrast, OTL combines a ray-tracing basis with solving Helmholtz wave equations to calculate the sound propagation. Therefore, the package could

[6] This section is identical to section 6.3.5.

be seen as an intermediate between traditional engineering and (full) wave-based acoustic models[28]. The model has a higher level of fidelity than ISO-9613, but keeps the calculation time reasonable[28,29]. The model considers the propagation paths in a three-dimensional space, which makes the model interesting for aircraft noise, which is more difficult to approach as a two-dimensional problem, as the position of the source changes in all three directions (x,y,z).

The model implements a range of calculation methods, based on publications and previous research. The basis, formed by a ray-tracing engine (to identify straight paths) [30] and image-source algorithm for the relevant detected paths (to identify reflections between surfaces)[31], is combined with diffraction[32,33] and reflection[34] coefficients for spherical waves. Surface properties are based on material impedance[35], while the model applies empirical standards for atmospheric attenuation[36] and turbulence[23,25,37]. Atmospheric refraction, simulated as ray curvature, is based on the Nord2000 method. The sound speed gradient can be set either as linear or as a linear approximation of a logarithmic profile, with the temperature, roughness constant, wind velocity and wind direction as the input parameters[38]. The model uses the following equation to calculate the sound pressure level at the position of the receiver ([28,29,39]):

$$p_{receiver} = \sum_{y=1}^{q} \sum_{n=1}^{n} p_y \frac{e^{jkR_i}}{R_i} \prod_{0=1}^{x} c_0 \qquad (7.1)$$

In this equation q refers to the number of sound sources, n refers to number of sound paths arriving at the receiver, p_y stands for the power level of the source(s), $\frac{e^{jkR_i}}{R_i}$ describes atmospheric attenuating due to spherical radiation, and $\prod_{0=1}^{x} c_0$ represents the coefficients describing diffraction, refraction and turbulence of the transmission path between the source and the receiver.

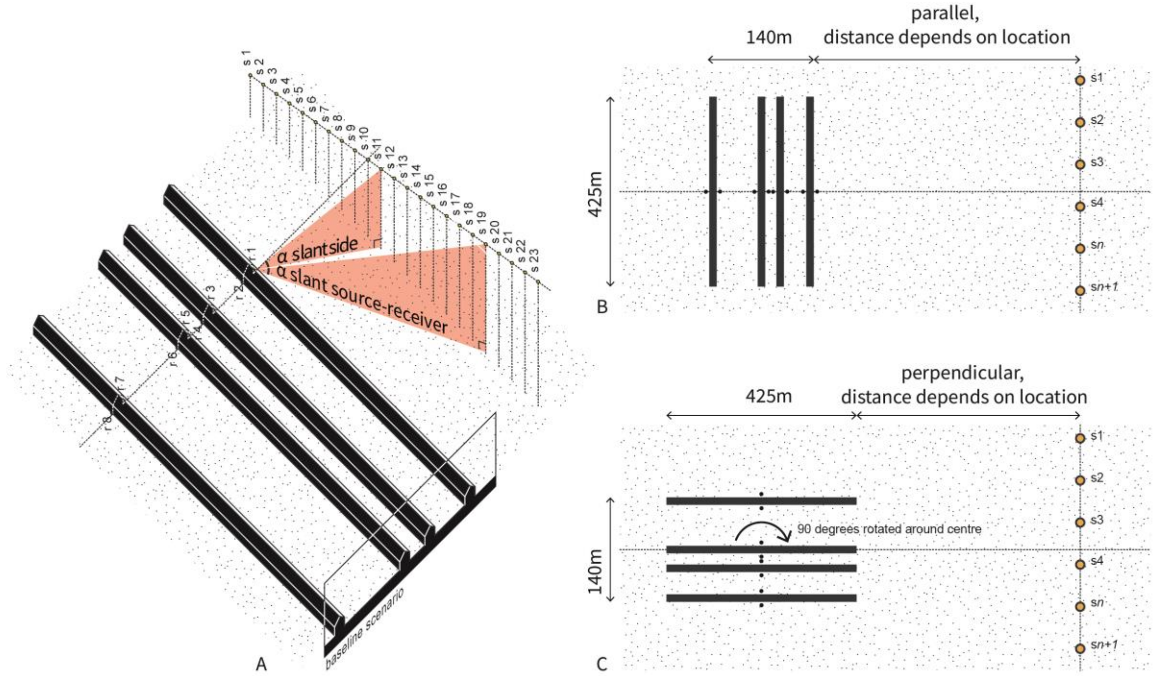

Figure 51 a) Axonometric impression of an aircraft flight path and the baseline scenario as inserted in the numerical model. For each location, the study considered the sound levels around the buildings for 20 individual source positions. The microphones are numbered 1 - 6 (r1, r2..). b) Top view of scenarios parallel to the flight paths. c) Top view of scenarios turned perpendicular to the flight paths.

7.3.4. Baseline scenario

As the urban layout is different for each location, an imaginary baseline variant was designed, which was similar for all three locations. The first microphone was placed at the same position as the positions of microphones A-1, B-1 and C-1 (see Figure in chapter 5 for more details). Figure 51 shows the baseline scenario inspired by a standard two-storey-building with a saddle-backed roof and an attic. To study the impact of canyon dimensions, the study calculated the sound levels around buildings for three canyon widths (15m, 30m and 55m), albeit only loosely (see Figure 52). This means that the position of the three canyon typologies are fixed and consecutive (see Figure 51), and the results for each intervention should be analysed for each width profile individually. Hence, caution should be observed in respect to interpreting the results across the different widths. The narrowest canyon corresponds to a street, while the other canyons are traditionally associated with gardens or wider urban blocks.

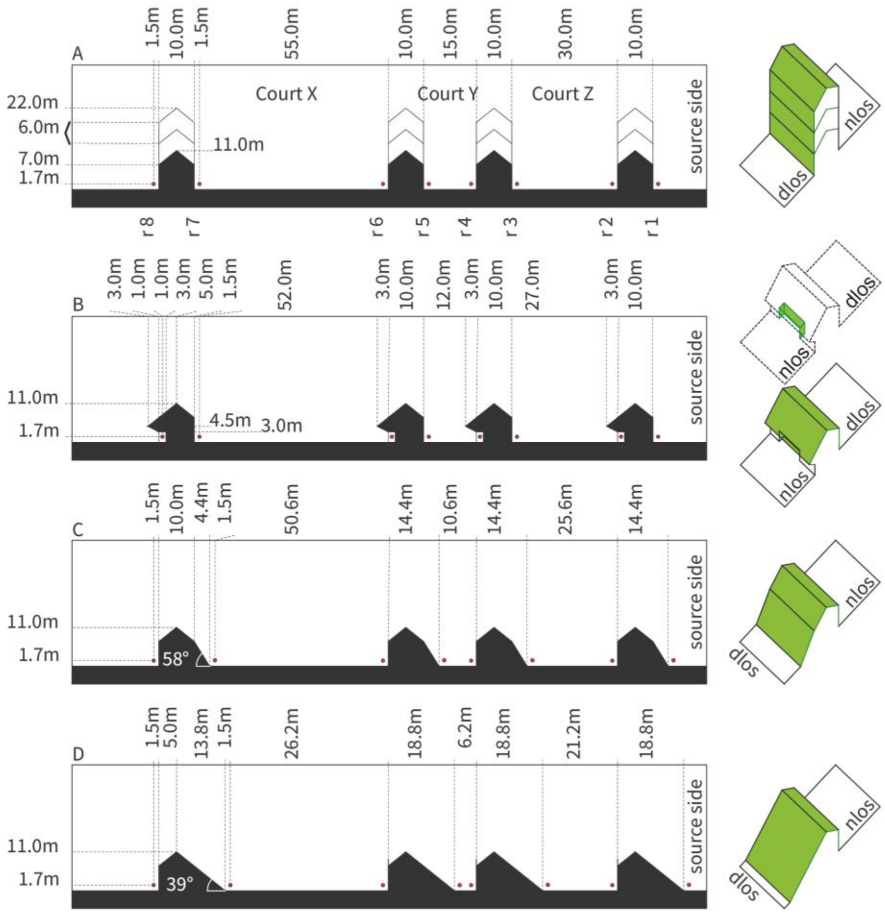

Figure 52 Sections and axometries of four design variables, i.e. see Figure 51 for street orientation as the fifth variable, as variations on the baseline scenario. The green planes and lines in the axonometries indicate the surfaces with green walls in the second phase of the experiment. A) increasing the building height by steps of 6m, B) overhanging roofs and loggias (the axonometry at the top indicate where green walls were added in the inset) C) tilted facade at an angle of 58° s, D) tilted facade at an angle of 39°.

7.3.5. Design variables

In total, five building design variables were selected for the study: 1) building height, 2) building orientation, 3) building protrusions, 4) street orientation and 5) surface cladding. For each parameter, the hypothesis was that the intervention would yield a significant positive effect compared to the baseline scenarios. Thus, the interventions were expected to increase the relative difference between an exposed and shielded facade and reduce the sound levels near shielded facades. In this paper, ‘exposed facades’ are building sides that face directly towards a flight path (*d*LOS side), whereas ‘shielded facades’ face directly away from a flight path (*n*LOS side). The terms shielded and *n*LOS, and exposed and *d*LOS, are used interchangeably in this paper. It was also expected that the impact of the interventions would be greater for smaller canyons than for the wider courts.

The parameter study was carried out in two steps. In the first step, the flow resistivity of the surface and ground materials was ‘hard’, which corresponded to rigid materials such as masonry, glass or concrete. The effective flow resistivity of the material was 20.000 kPa/m^2·s. In the second step, the flow resistivity of several surfaces was changed to a value comparable to the green substrates used for vegetation walls on buildings (see Figure 52). The effective flow resistivity of this material was 100 kPa/m2·s. Ground surfaces were kept as 'hard'. A comparison with relevant literature showed that the properties this study used for a green wall were conservative in respect to the acoustic effects other studies measured of green walls in-situ[18,38,39]. In total, 19 design variations on the baseline scenarios were made and examined. The effects of the design variants were studied for octave bands (OBs from now on) between 63Hz and 1000Hz. The building geometry parameters are discussed in more detail below.

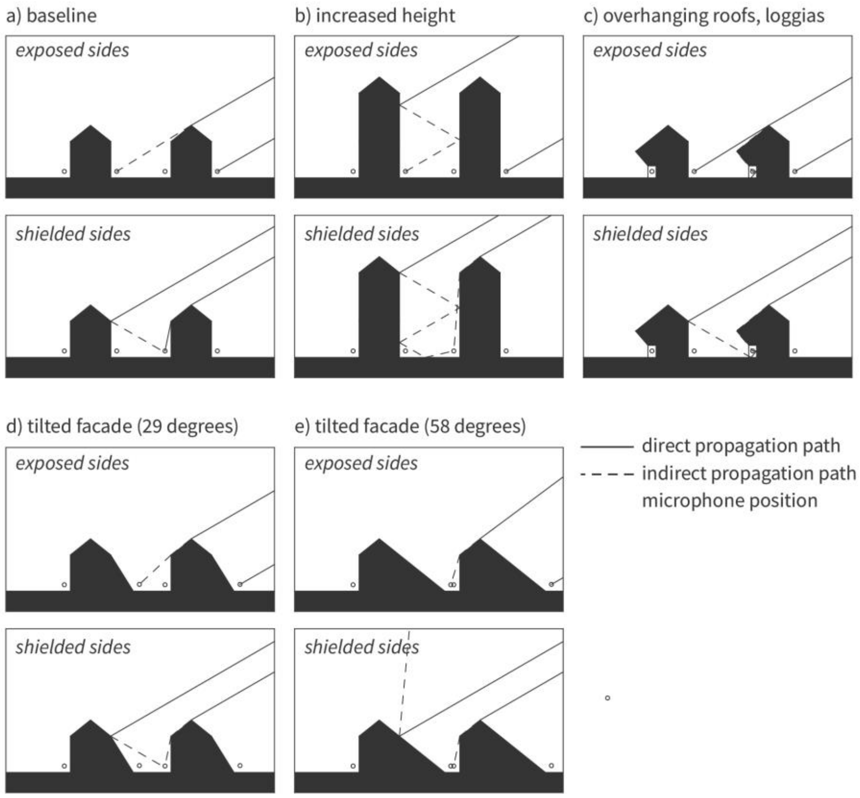

Figure 53 Schematic analysis of direct and reflected / diffracted propagation paths for the five parameters.

7.3.5.1. *Building height*

Literature shows that sound levels behind the obstacle drop when the height of a building or barrier increases[40,41]. Taller buildings extend the path length between a source and receiver, which applies to both direct and diffracted waves (see Figure 53b). In this study, the building height was increased by 6m twice. The jump in height corresponds to two extra floors placed on top of the buildings (see Figure 52a). The maximum building height considered in this study was 22m, which represents the six-storey building common in European city centres.

7.3.5.2. Building protrusions and loggias

Literature shows that facade ornaments and balconies diffuse the sound field between buildings[12,15,16]. Since aircraft noise reaches a roof from above, the noise abating potential of rooftops (caused by diffraction and surface scattering) will be smaller for aircraft noise than for road or rail noise (see Figure 53c). Figure 52b shows the design with a protruding or overhanging roof and loggias with microphones placed inside the insets, 1m away from the original building line.

7.3.5.3. Facade orientation

The orientation of facades, i.e. the angle at which a facade is tilted, may reflect the incident sound waves away from the (shielded) facade (see Figure 53d-e). A previous study suggested that the orientation of the facade reflects aircraft noise towards the sky instead of the receiver[12]. Therefore, the study considered two scenarios in which the orientation of the exposed facades was changed. The facade was tilted at two angles (39° and 58°), see Figure 52 and Figure 53d-e.

7.3.5.4. Street orientation

The street orientation was varied by rotating the entire urban configuration 90 degrees around its centre (see Figure 51c). The hypothesis was that by rotating the canyons perpendicular to the flight paths, the maximum sound level would be higher compared to the baseline scenarios. However, the assumption was that the sound would decay faster due to the extra shielding by the buildings from both sides.

7.3.6. Analyses

7.3.6.1. Parameter study

The results of the design variants were compared to the results of the baseline scenarios for OBs between 63Hz and 1000Hz. The following three factors were analysed:

1. The maximum difference between a facade facing directly towards a flight path (exposed) and a facade facing directly away from it (shielded) (ΔL_{max})
2. The average difference between a facade facing directly towards and away from a flight path (ΔL_{eq})
3. The sound level near facades facing directly away from a flight path

The first factor is the maximum difference in sound levels between the two facades. The second factor is the difference between the facades, but for the equivalent sound level during the aircraft flyovers, i.e. the average of the 20 source positions.

The following equation defines the equivalent sound pressure per microphone:

$$L_{eq} = 10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_p(t)}{10}} d(t)\,\Delta_{ni}\right) \tag{7.2}$$

In the equation, $L_p(t)$ refers to the sound pressure level per position or instant, and n refers to the total number of positions considered, i.e. 20 for each location in this study. Subsequently, the equivalent sound pressure levels near both facades were subtracted to calculate ΔL_{eq}. Finally, the results of the baseline scenarios were subtracted from the results of a variant. Positive values indicate that a variant increased the noise reduction around a building.

The first and second factors were used to analyse the relative sound abatement induced by a design intervention compared to the baseline scenario. In relation to road traffic noise, studies show that the relative difference between exposed and non-exposed facades can reduce noise annoyance[42,43]. The third factor was used to analyse to what extent a variant had an added sound-reducing effect near shielded facades. The results were studied for each of the canyon width typologies separately. As the results were non-parametric, a series of Kruskal-Wallis and/or Whitney-Mann U with Bonferroni post hoc tests were carried out. The results of these tests were used to examine whether the observed differences were statistically significant.

7.3.6.2. Aircraft noise abating potential around the case study sites

After the parameter study, the numerical results were used to examine the implications for the three case study locations. Only interventions that had shown a clear significant noise abating effect were considered for the final part of the study. For the analyses, the results measured at three exposed and three shielded microphones were taken as reference (see Figure). For the exposed positions, A-1, B-1 and C-4, the mean peak level during aircraft flyovers was taken. To determine the minimum threshold below which the ambient sound level masks the aircraft noise, the average sound level, as measured at intervals between aircraft flyovers at the positions A-2, B-2 and C-5, was used. The analysis focused on the abating effects for the 63Hz, 125Hz and 500Hz OBs. In addition, the analysis only focused on the results for the widest and the most narrow canyons.

7.4. Results

7.4.1. Baseline scenarios and green walls

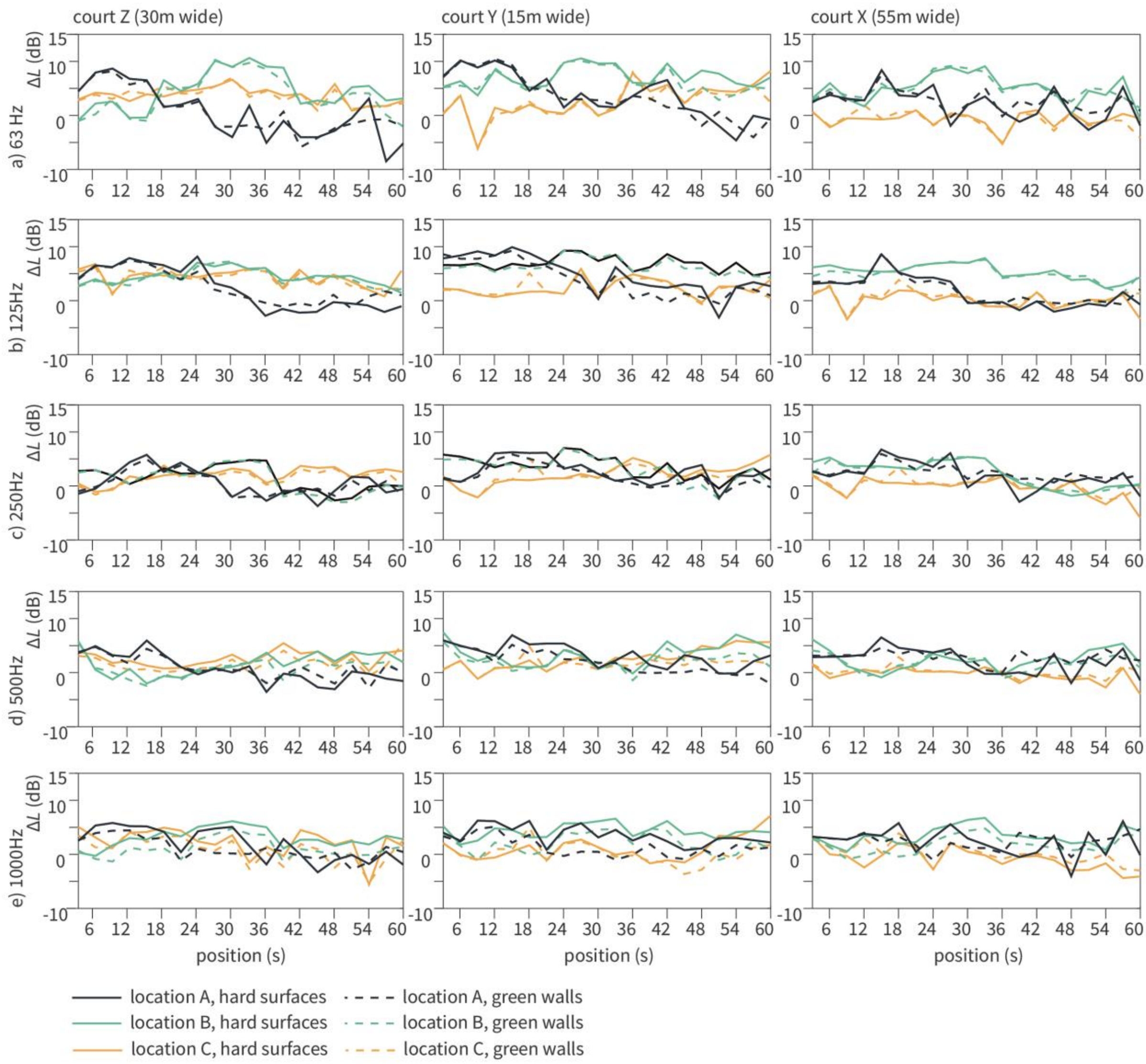

Figure 54 Differences between shielded and exposed facades (ΔL) for the baseline scenarios (solid lines), and the baseline scenarios with green walls (dashed lines). Results are plotted for each aircraft position and only for the 250Hz octave band.

Table 13 Results for Whitney-Mann U tests per octave band for each canyon width and location (A,B,C), comparing hard surfaces and green walls for the baseline scenarios.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	U	*194*	168	193	184	179	171	189	189	157	176	155	121	165	88	115
	p	.883	.398	.862	.678	.583	.445	.779	.779	.253	.529	.231	.033	.365	**.002**	**.021**
Y	*U*	194	139	178	156	147	197	146	182	177	129	142	121	74	77	159
	p	.883	.102	.565	.242	.157	.947	.149	.640	.547	.056	.121	.033	**>.001**	**.001**	.277
X	*U*	177	189	190	181	178	163	168	196	168	179	171	155	187	107	140
	p	.547	.779	.799	.620	.565	.327	.398	.925	.398	.583	.445	.231	.738	**.011**	.108

Table 14 Results for Whitney-Mann U tests per octave band for each canyon width and location (A,B,C) for *n*LOS positions only, comparing hard surfaces and green walls for the baseline scenarios.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	U	*156*	195	168	149	183	175	141	169	181	159	176	186	171	186	183
	p	.242	.904	.398	.174	.659	.512	.114	.414	.620	.277	.529	.718	.445	.716	.659
Y	*U*	147	199	183	184	191	159	169	185	171	184	188	182	184	195	178
	p	.157	.989	.659	.678	.820	.277	.414	.698	.445	.678	.758	.640	.678	.904	.565
X	*U*	119	169	185	140	182	166	142	167	145	172	181	176	185	189	162
	p	**.028**	.414	.698	.108	.640	.369	.121	.383	.142	.461	.620	.529	.698	.779	.314

The first analysis focused on the impact of green walls. The results of the baseline scenarios, with hard surfaces, were compared to scenarios with surface greening added to the baseline configuration. Figure 54 shows the difference in sound levels between exposed and shielded facades plotted for each position for the 250Hz OB. The results of the Whitney-Mann U and Bonferroni post hoc tests are given in Table 13 and Table 14. In terms of the relative sound abatement around buildings, Table 13 shows that green walls have a significant effect for the 1000Hz OB at all three locations. However, the results in Table 14 show that these effects should be attributed to a reduction in sound levels near the exposed facades. This means that the added vegetation did not significantly reduce the sound level near shielded facades.

7.4.2. Building height

Table 15 Results for the ΔL_{max} between the baseline scenarios and the interventions (I). H1 refers to a building height 6m higher than the baseline scenario, H2 to a building height 12m higher than the baseline scenario, G refers to green walls. Results are given per octave band and for each canyon width (C) (X, Y and Z), and per location (A,B,C), given in dB.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	H1	5	6	3	4	9	4	5	11	4	5	8	3	7	14	5
	H1G	7	8	3	8	13	4	11	16	4	13	16	2	18	22	5
	H2	6	9	17	7	10	23	5	12	26	11	8	25	13	7	30
	H2G	6	8	11	7	13	13	6	18	15	13	18	15	16	24	18
Y	H1	8	2	-2	10	3	4	15	3	2	18	-3	1	23	-4	-2
	H1G	14	3	-2	18	4	4	23	2	2	25	-5	1	30	-7	-1
	H2	11	5	17	12	4	25	14	6	25	18	6	26	22	8	23
	H2G	8	7	15	13	2	21	15	5	20	19	5	20	26	7	21
X	H1	0	4	7	0	5	4	5	9	5	8	11	6	13	12	4
	H1G	5	6	6	6	8	5	13	14	5	15	18	6	19	21	5
	H2	1	2	12	-1	6	11	3	12	10	6	15	13	8	18	12
	H2G	2	4	12	0	10	12	4	15	12	7	19	15	11	22	16

Table 16 Results for the ΔL_{eq} between the baseline scenarios and the interventions (I). H1 refers to a building height 6m higher than the baseline scenario, H2 to a building height 12m higher than the baseline scenario, G refers to green walls. Results are given per octave band and for each canyon width (C) (X, Y and Z), and per location (A,B,C), given in dB.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	H1	2	2	2	1	4	1	2	3	1	0	5	0	-2	6	-5
	H1G	2	3	1	1	4	1	2	4	1	3	5	0	2	5	-3
	H2	3	2	5	2	3	5	3	3	5	2	4	5	-1	2	7
	H2G	3	4	5	3	6	5	3	6	6	4	7	6	2	6	9
Y	H1	-3	0	0	0	1	2	1	-1	2	-3	-5	3	-3	-6	4
	H1G	-2	0	1	-1	1	2	1	0	2	1	-3	2	2	-3	4
	H2	-2	-2	5	-1	-2	6	1	0	7	2	3	9	3	3	14
	H2G	-2	-1	5	-1	-2	6	1	1	7	3	3	10	6	3	14
X	H1	-1	-5	4	-1	-2	3	0	-1	2	1	3	2	3	2	2
	H1G	1	-4	4	1	-2	3	1	0	3	3	4	3	4	3	4
	H2	-1	-2	5	-1	0	4	-2	2	4	-1	7	-1	-1	9	-2
	H2G	0	0	6	1	2	5	0	4	5	1	9	1	1	11	1

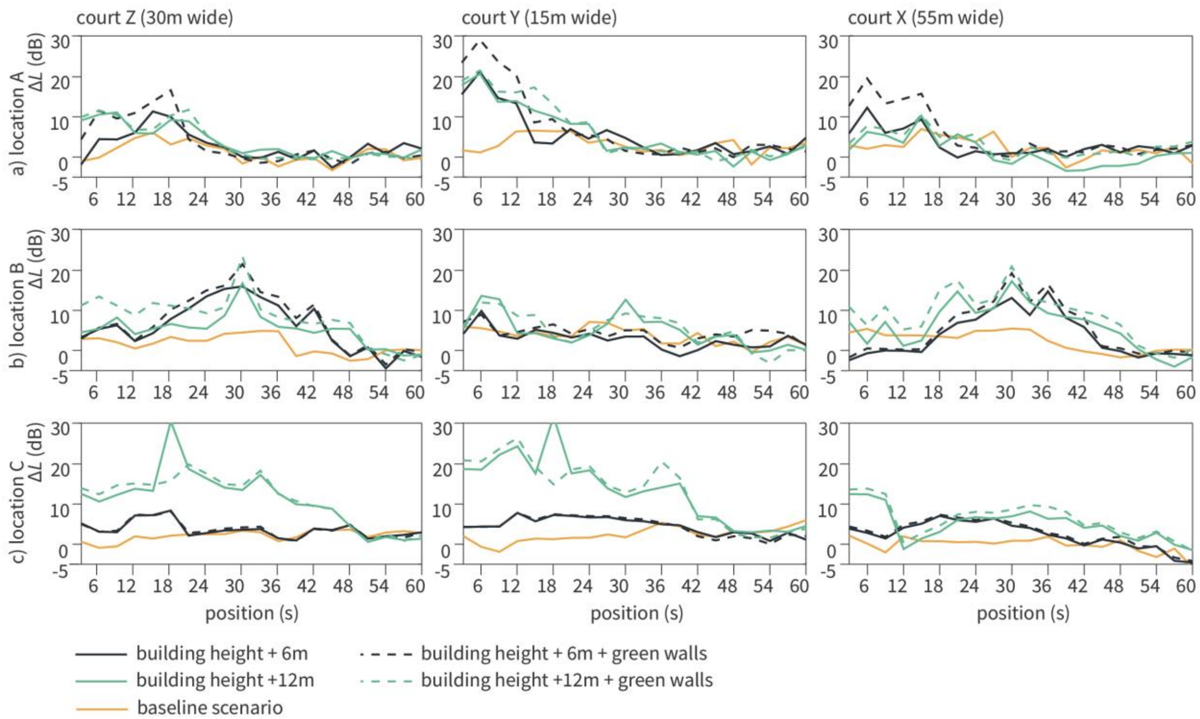

Figure 55 Differences between shielded and exposed facades (Δ*L*) for the baseline scenarios, and incremental height increases by 6m and 12m, and/or combined with green walls. Results are plotted for each aircraft position, only for the 250Hz OB.

Table 15 and Table 16 show the ΔL_{max} and ΔL_{eq} for each intervention, expressed as the difference when compared to the baseline scenarios. Figure 55 plots the results per position for the 250Hz OB. Table 15 shows that when increased building height and green walls are both employed, the difference between shielded and exposed facades can increase by an extra >25dB for OBs above 125Hz, compared with the baseline scenarios. The table shows that this added difference between the exposed and shielded facades increases together with the sound frequency. Hence, the relative effect of the interventions is smaller for lower frequencies, although it is still substantial. Table 15 and Figure 55 show that the impact of the interventions, i.e. the difference in sound level between both facades, also depends on the canyon width. The interventions yielded a greater effect for the smallest canyon (Court Y) than for the other two canyon typologies. The figures also show that the relative increase of the difference between two facades is greater for location C than for location A or B. This can be attributed to location C's distance from the flight path and the angle of incidence of the sound front. For waves to reach the receiver, the number of reflections occurring between facades will be greater for location C than the other two sites, especially location B. Hence, the noise abating effect of taller buildings is stronger for this site compared to the other two locations.

Table 16 shows that, considering the overall equivalent noise abatement, the effects are not always positive. When frequencies were <250Hz and the canyon was narrow, the overall effects of the interventions can be negative for location A and B. This means that the equivalent sound level increases for an intervention compared to the baseline scenarios. Figure 55 suggests that, in some situations, the intervention only has a strong noise abating effect when the position of the source is perpendicular to the microphones. This causes the ΔL_{max} to peak, but does not change the sound levels for most of the flight trajectory. Moreover, reflections against taller buildings can resonate between the buildings, increasing the secondary sound levels within the canyon. This effect is stronger for lower frequencies, as the materials absorb less of the incident sound energy.

To estimate the statistical significance of the induced effects, a series of Kruskal-Wallis tests with Bonferroni post hoc corrections were carried out (see Table 16 and Table 17). Table 16 shows that the relative difference between facades is often significant, except for location A. This means that for location A, the relative difference between exposed and shielded facades is not significantly different from the baseline scenarios for any of the canyon typologies. For location B, the difference between building sides is only significant for wider canyon topologies, i.e. Z and X, or OBs >250Hz for the narrow canyon. For location C, the effects were significant for all canyon topologies and frequencies.

To examine the abating effects of the interventions near shielded facades, a second series of statistical tests was performed on the data. Table 17 shows that the interventions yielded a significant effect for most frequencies, except for OBs <250Hz for location B. For wide canyon typologies, the results show that the tallest building variant combined with green walls, had the strongest noise reducing effect over a wide range of frequencies. For a narrow canyon, the results show that a height increase in combination with green walls was only significant for location A and C, for OBs <500Hz. This might be attributed to reflections within the canyon and the angle of incidence. For location B, the altitude of the aircraft is substantially higher when they fly by compared to location A. Although the altitude of the aircraft is higher for location C, the horizontal distance between the ground track and location C is greater than for location B. Hence, the relative angle of incidence of the incoming sound waves is greater for location B than for location A and C. Reflections against the wall can simply reach the ground level and the walls hardly absorb the sound energy of the reflected sound. Consequently, this might negate the noise attenuation realized by edge diffraction. Because the green wall does not abate lower frequencies well enough, the surface material only reduces the surface reflections for higher frequencies. However, it can be concluded that the interventions yield a significant general noise abating effect compared to the baseline scenarios, particularly for wider canyon typologies.

Table 17 Results for Kruskal-Wallis and Bonferroni post hoc tests per octave band for each canyon width (X, Y Z) and location (A, B, C). B refers to Baseline scenario(s), H1 refers to a building height 6m higher than the baseline scenario, H2 to a building height 12m higher than the baseline scenario, G refers to green walls.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	X^2	*4.057*	10.180	27.704	4.279	26.216	30.215	4.214	19.102	33.853	4.414	28.703	23.871	1.734	13.732	24.011
	p	.398	.037	>.001	.370	>.001	>.001	.378	.001	>.001	.353	>.001	>.001	.784	.008	>.001*
	B-H1		.038			>.001			.006			.001			.005	
	B-H2			>.001		.011	>.001		.013	>.001		.001	.002			.019
	B-H1G		.028			>.001			>.001			.026			.025	
	B-H2G		.003	>.001		>.001	>.001		>.001	>.001		>.001	.001		>.001	.006
	H1-H2			.007			.005			.004			.005			.001
	H1-H2G			.007			.003			.001			.003			>.001
	H1G-H2			.005			.003			.006			.001			.002
	H1G-H2G			.005			.001			.002			.001			.001
	H2-H2G					.046									.039	
Y	X^2	.931	1.748	25.699	.924	12.170	38.367	1.300	7.279	38.644	5.535	49.972	24.577	3.873	60.207	35.249
	p	.920	.782	>.001	.921	.016*	>.001	.861	.122	>.001	.237	>.001	>.001	.423	>.001	>.001
	B-H1									.030		.001			>.001	.033
	B-H2			>.001			>.001			>.001		.036	>.001			>.001
	B-H1G									.040		.016			.002	.019
	B-H2G			.001			.001			>.001		.050	>.001			>.001
	H1-H1G														.036	
	H1-H2			.001			.001			.002		>.001	.026		>.001	.008
	H1-H2G			.006			.001			.005		>.001	.020		>.001	.003
	H1G-H2			.001			.002			.002		>.001	.018		>.001	.016
	H1G-H2G			.008			.003			.003		>.001	.014		>.001	.006
X	X^2	4.685	11.369	35.150	5.640	10.674	31.611	7.313	14.419	29.041	8.185	14.930	15.140	3.835	15.714	17.745
	p	.321	.023	>.001	.228	.030	>.001	.120	.006	>.001	.085	.005	.004	.429	.003	.001
	B-H1			>.001			.003			.019			.014			.033
	B-H2			>.001			>.001		.039	>.001		.016			.033	
	B-H1G			.001			.001			.006		.049	>.001			.001
	B-H2G			>.001		.026	>.001		.001	>.001		>.001	.001		.001	.001
	H1-H2G		.003			.002	.034		.003	.009		.010			.002	
	H1G-H2G		.011	.049		.016			.042	.030					.030	.010
	H2-H2G					.034										.008

Table 18 Results for Kruskal-Wallis and Bonferroni post hoc tests per octave band for each canyon width (X, Y, Z) and location (A,B,C). B refers to Baseline scenario(s), H1 refers to a building height 6m higher than the baseline scenario, H2 to a building height 12m higher than the baseline scenario, G refers to green walls.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	X^2	*30.167*	19.274	69.907	30.941	44.428	71.351	22.691	39.832	71.336	13.896	40.783	70.947	7.744	37.486	71.147
	p	>.001	.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	.008	>.001	>.001	.101	>.001	>.001
	B-H1	.017	.004	>.001		.001	>.001		>.001	>.001		>.001	>.001		>.001	>.001
	B-H2	.003	.002	>.001	.008	.001	>.001	.016	>.001	>.001		.003	>.001			>.001
	B-H1G	>.001	.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	.003	>.001	>.001		>.001	>.001
	B-H2G	>.001	>.001	>.001	.001	>.001	>.001	.003	>.001	>.001	.004	>.001	.001		>.001	.001
	H1-H2			.001	.032		.001			.001			.002			.002
	H1-H2G			>.001	>.001	.011	>.001	.021	.010	>.001	.031		>.001			>.001
	H1-H1G	.005			>.001			.005			.024					
	H1G-H2	.025		.003			.002			.005		.043	.009		.002	.014
	H1G-H2G			.001			>.001			.001			>.001			>.001
	H2-H2G								..008			.004			.002	
Y	X^2	14.197	7.388	72.888	15.240	7.799	78.036	14.197	7.388	72.888	13.194	46.244	82.618	11.468	51.736	77.858
	p	.007	.117	>.001	.004	.099	>.001	.001	.117	>.001	.010	>.001	>.001	.022	>.001	>.001
	B-H1			>.001			>.001			>.001		.023	>.001		.004	>.001
	B-H2			>.001			>.001			>.001		.009	>.001		0.029	>.001
	B-H1G	.037		>.001	.001		>.001	.037		>.001	.009		>.001	.015		>.001
	B-H2G			>.001	.003		.001			>.001	.002	.001	.001	.003	>.001	.002
	H1-H2			.001			>.001			>.001		>.001	>.001		>.001	>.001
	H1-H2G	.003		>.001	.034		>.001	.003		>.001	.016	>.001	>.001	.031	>.001	>.001
	H1-H1G	.001			.016			>.001			.049					
	H1G-H2			.001			>.001			.001		>.001	>.001		.001	.001
	H1G-H2G			.001			>.001		.002	>.001		>.001	>.001		>.001	>.001
X	X^2	22.386	33.002	58.685	23.853	44.617	55.567	17.412	39.806	61.207	13.887	44.715	49.909	8.492	49.771	50.481
	p	>.001	>.001	>.001	>.001	>.001	>.001	.002	>.001	>.001	.008	>.001	>.001	.075	>.001	>.001
	B-H1			>.001		.005	>.001		.017	>.001		.003	>.001		.006	>.001
	B-H2		.001	>.001	.021	.001	>.001		>.001	>.001		>.001	>.001		>.001	>.001
	B-H1G	>.001	.020	>.001	>.001	>.001	>.001	>.001	.001	>.001	.001	>.001	>.001		>.001	>.001
	B-H2G	>.001	>.001	>.001	>.001	>.001	>.001	.005	>.001	>.001	.008	>.001	>.001		>.001	>.001
	H1-H1G	.009			.019			.045								
	H1-H2			.025						.021						
	H1-H2G		>.001	.005	.011	>.001	.011		>.001	.001		.001			>.001	
	H1G-H2	.023						.004			.019					
	H1G-H2G	.049	>.001	.017		.002	.044		.007	.010		.015			.004	
	H2-H2G		.033			.019		.039				.040			.010	

7.4.3. Facade orientation (angle)

Table 19 Results for the ΔL_{max} between the baseline scenarios and the interventions (I). T1 refers to a facade tilted at 39°, T2 to a facade tilted at 58°, G refers to green walls. Results are given per octave band and for each canyon width (C) (X, Y, Z), and per location (A, B, C), given in dB.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	T1	-5	2	1	-4	-1	4	-3	-3	2	-3	-1	2	-2	0	3
	T2	-5	0	0	-4	0	2	-3	0	1	-2	-1	0	-2	-1	1
	T1G	-3	-3	1	-4	-3	1	-2	-4	0	-1	-4	0	-1	-4	-1
	T2G	-3	-2	0	-3	-4	1	-2	-5	0	-1	-4	0	-2	-5	1
Y	T1	-6	2	4	-5	1	2	-3	3	4	-3	4	2	-2	3	4
	T2	-6	-1	0	-5	-1	1	-3	1	1	-3	-1	0	-2	-3	0
	T1G	-4	-3	0	-5	-5	0	-3	-1	1	-3	-2	-1	-1	-4	1
	T2G	-6	-3	2	-4	-4	1	-3	-1	1	-2	-2	-1	-1	-4	0
X	T1	-4	3	-4	-5	3	0	-4	2	0	-2	1	-1	-3	1	0
	T2	-5	-1	0	-5	0	0	-3	0	1	-3	-2	0	-2	-3	1
	T1G	-3	-1	0	-4	0	1	-3	0	0	-3	-1	0	-2	-2	1
	T2G	-4	-2	-1	-3	-1	0	-2	-1	1	-2	-2	0	0	-3	0

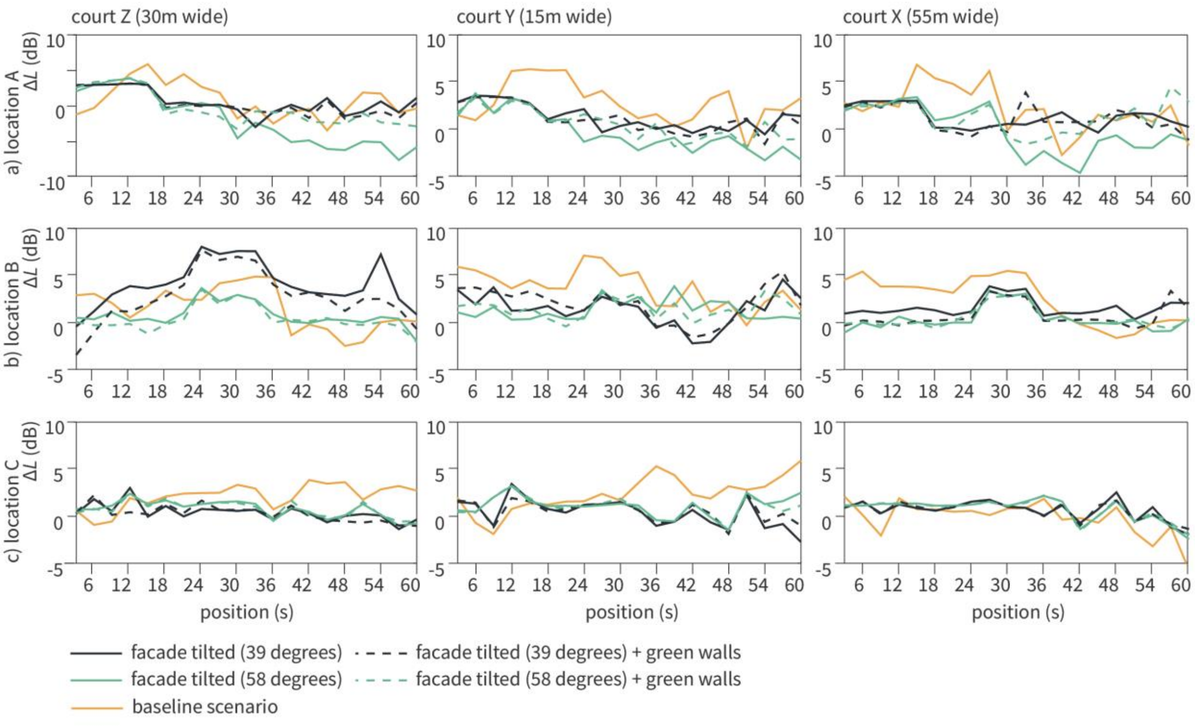

Figure 56 Differences between shielded and exposed building sides (ΔL) for the baseline scenarios with facades tilted at two angles, and the baseline with facades tilted under two different angles and green walls. Results are plotted for each aircraft position and only for the 250Hz octave band.

Table 20 Results for the ΔL_{eq} between the baseline scenarios and the interventions (I). T1 refers to a facade tilted by 39°, T2 to a facade tilted by 58°, G refers to green walls. Results are given per octave band and for each canyon width (C) (X, Y, Z), and per location (A, B, C), given in dB.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	T1	0	2	-4	-3	1	-3	-1	2	-2	-1	3	-1	-2	0	-1
	T2	2	1	-4	-1	0	-3	1	1	-2	1	2	-1	-1	-1	-2
	T1G	-3	-3	-3	-4	-3	-4	-2	-1	-1	-1	0	-2	-1	-2	-2
	T2G	-1	-3	-3	-3	-3	-4	-1	-1	-1	-1	0	-2	-2	-2	-1
Y	T1	-3	-2	-2	-4	-2	-2	-2	-3	-2	-2	0	-1	-2	-1	0
	T2	-1	-2	-2	-2	-2	-2	-1	-2	-2	-1	-1	-2	-1	-2	1
	T1G	-6	-5	-2	-6	-6	-2	-3	-3	-1	-2	-2	-1	-1	-3	1
	T2G	-4	-5	-2	-4	-5	-2	-2	-3	-1	-2	-2	-1	-2	-3	1
X	T1	-1	-2	1	-1	-4	1	-1	-2	1	-2	-1	1	-1	-3	1
	T2	-2	-4	1	0	-5	1	-1	-2	1	0	-1	1	0	-3	1
	T1G	-3	-4	1	-1	-5	1	-3	-3	1	-2	-1	1	-1	-3	1
	T2G	-2	-5	1	-1	-5	1	-2	-3	1	-1	-1	1	-1	-3	1

The second analysis focused on the noise abating effect of the facade orientation either alone or in combination with green surfaces. Table 19 shows the results of the ΔL_{max} per intervention compared to the baseline scenarios. The table shows that, for most frequencies and canyon profiles, the interventions had a negative effect on the maximum difference between the shielded and exposed facades. Table 20 and Figure 56 shows that the negative effect applies for most source positions, resulting in lower ΔL_{eq} values for nearly all cases studied. The results suggest that there is no clear difference between wide and narrow canyons in this respect.

To examine the statistical significance of the results, a series of Kruskal-Wallis and Bonferroni post hoc tests was carried out. Table 20 shows that, for a narrow canyon, the relative decrease of the sound levels between the facades is significant for most situations. However, the results are ambiguous and mixed for the two wider canyon typologies. For example, for a canyon width of 30m, results are not significant for location A, but are significant for location C. The results suggest that this is reversed for a canyon width of 55m. Only for location B, the results show the interventions to have a consistent significant effect across the octave bands analysed. Table 22 shows that the interventions did not have a significant effect on the sound levels near shielded facades, except for OBs <500Hz for location A. For location A, a moderate rotation of the facade, either alone or combined with vegetation, seems to reduce the sound level near exposed facades for lower frequencies. This means that the significant effects in Table 21 should be attributed to a reduction of the sound levels near the exposed facades, hence the negative values in Table 20 and Table 21. The results are likely caused by a combination of the ray-tracing character of the model, and a gradual change of the source positions. This means that the angle of incidence and the specular reflections against the tilted facades are responsible for the volatility of the results. If a ray just hits the right angle, the sound is reflected outward from the canyons, while for other angles the reflections are directed inward. Moreover, the positions of the exposed microphones were adjusted to conform to the 1.5m distance between a microphone and a facade. Although close to each other, this means that the positions of the exposed microphones were not the same for the three scenarios. This may have caused variations in the sound pressure levels that are not related to the shape of the facades, but to the location of the microphone within the canyon instead.

Table 21 Results for Kruskal-Wallis and Bonferroni post hoc tests per octave band for each canyon width (X, Y, Z) and location (A, B, C). B refers to baseline scenario(s), T1 to a tilted facade by 39°, T2 to a tilted facade by 58° and G to green walls.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	X^2	5.864	45.195	34.822	5.593	59.005	36.665	10.098	31.496	25.484	8.466	30.360	32.999	5.588	15.773	12.270
	p	.210	>.001	>.001	.232	>.001	>.001	.039	>.001	>.001	.076	>.001	>.001	.232	.003	.015
	B-T1		.039	>.001			>.001		.002	>.001		.012				
	B-T2		.003	>.001		>.001	>.001	.021		.003			>.001		.009	.002
	B-T1G			>.001			>.001			>.001			.036		.021	.006
	B-T2G		.002	>.001		>.001	>.001		.044	.002			>.001		.002	.013
	T1-T1G														.043	
	T1-T2		>.001			>.001		.033	>.001			>.001	.002		.020	
	T1-T2G		>.001			>.001			>.001			>.001	.001		.006	
	T1G-T2		>.001			>.001		.011	.021				.012			
	T1G-T2G		>.001			>.001			.001				.011			
Y	X^2	21.749	59.369	12.438	22.209	67.880	8.998	22.701	19.923	18.494	14.788	19.811	17.576	18.775	45.677	2.436
	p	>.001	>.001	.014	>.001	>.001	.061	>.001	>.001	>.001	.005	.001	>.001	.001	>.001	.656
	B-T1		.028	.004	.004	.008	.019	.040	.006	>.001	.004		.003	.001		
	B-T2	>.001	>.001	.022	>.001	>.001	.018	>.001	.001	.006	.001	>.001	>.001	>.001	>.001	
	B-T1G			.001	.005	.046	.018	.019		>.001	.009	.034	.006	.001	>.001	
	B-T2G	.002	>.001		.002	>.001	.016	.001	.005	.016	.002	.001		.001	>.001	
	T1-T2	.003	>.001			>.001		.013				.004			>.001	
	T1-T1G														.001	
	T1-T2G		>.001			>.001						.016			.001	
	T1G-T2	.016	>.001			>.001		.028								
	T1G-T2G		>.001			>.001										
X	X^2	12.139	41.128	6.106	1.813	52.935	6.351	7.678	24.037	7.092	9.333	25.418	14.900	7.821	38.932	14.002
	p	.016	>.001	.191	.770	>.001	.174	.104	>.001	.131	.053	>.001	.005	.098	>.001	.007
	B-T1					.002							.002		.004	.003
	B-T2	.005	>.001			>.001			.001			>.001	.002		>.001	.003
	B-T1G	.007	>.001			>.001			.030			.002	.007		>.001	.003
	B-T2G		>.001			>.001			.002			>.001	.002		>.001	.004
	T1-T2		.001			.002			>.001			.003			.006	
	T1-T1G		.003			.025			.010			.030				
	T1-T2G		.001			.012			>.001			.004				

Table 22 Results for Kruskal-Wallis and Bonferroni post hoc tests per octave band for each canyon width (X, Y, Z) and location (A, B, C). B refers to baseline scenario(s), T1 to a tilted facade by 39°, T2 to a tilted facade by 58° and G to green walls.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	X^2	53.152	3.413	1.838	16.461	12.806	.496	20.935	5.460	.439	6.819	1.754	.104	1.844	1.513	1.591
	p	>.001	.491	.766	.002	.012	.974	>.001	.243	.979	.146	.781	.999	.764	.824	.810
	B-T1	>.001			.006			.003								
	B-T2					.002										
	B-T1G	>.001			.005			.002								
	B-T2G	.002				.005		.025								
	T1-T2	>.001			.004			.001								
	T1-T2G	.018														
	T1G-T2	>.001			.003			.001								
	T2-T2G	.003						.011								
Y	X^2	39.521	2.959	.372	21.724	2.171	1.981	12.661	4.360	.342	4.591	.410	.157	1.602	.241	.943
	p	>.001	.565	.985	>.001	.704	.739	.013	.360	.987	.332	.982	.997	.809	.993	.918
	B-T1	.003														
	B-T2	.010			.007											
	B-T1G	.011														
	T1-T2	>.001			>.001			.002								
	T1-T2G	.005														
	T1G-T2	>.001			>.001			.005								
	T1G-T2G	.016														
	T2-T2G	.007			.018			.016								
X	X^2	31.845	2.383	5.713	15.181	.535	4.192	13.528	1.052	5.989	3.935	.234	2.859	1.587	.065	2.354
	p	>.001	.666	.222	.004	.970	.381	.009	.902	.200	.415	.994	.582	.811	.999	.671
	B-T1	>.001			.002			.042								
	B-T1G	.039			.048											
	T1-T2	>.001			.001			.002								
	T1-T2G	.006			.034			.004								
	T1G-T2	>.001			.037											
	T2-T2G							.021								

7.4.4. Building protrusions

Table 23 Results for the ΔL_{max} between the baseline scenarios and the interventions (I). P refers to scenarios with protruding roofs and bays, G refers to green walls. Results are given per octave band and for each canyon width (C) (X, Y, Z), and per location (A, B, C), given in dB.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	P	4	-2	7	6	6	11	6	6	11	12	8	13	17	15	14
	PG	5	0	9	7	7	13	10	8	17	16	9	19	22	15	20
Y	P	4	2	1	6	3	6	9	3	6	13	3	8	17	11	7
	PG	3	4	3	6	6	7	10	6	7	12	5	11	17	13	13
X	P	3	10	1	6	14	7	12	16	12	16	16	11	19	24	12
	PG	5	13	7	9	13	14	13	18	16	17	19	18	23	26	19

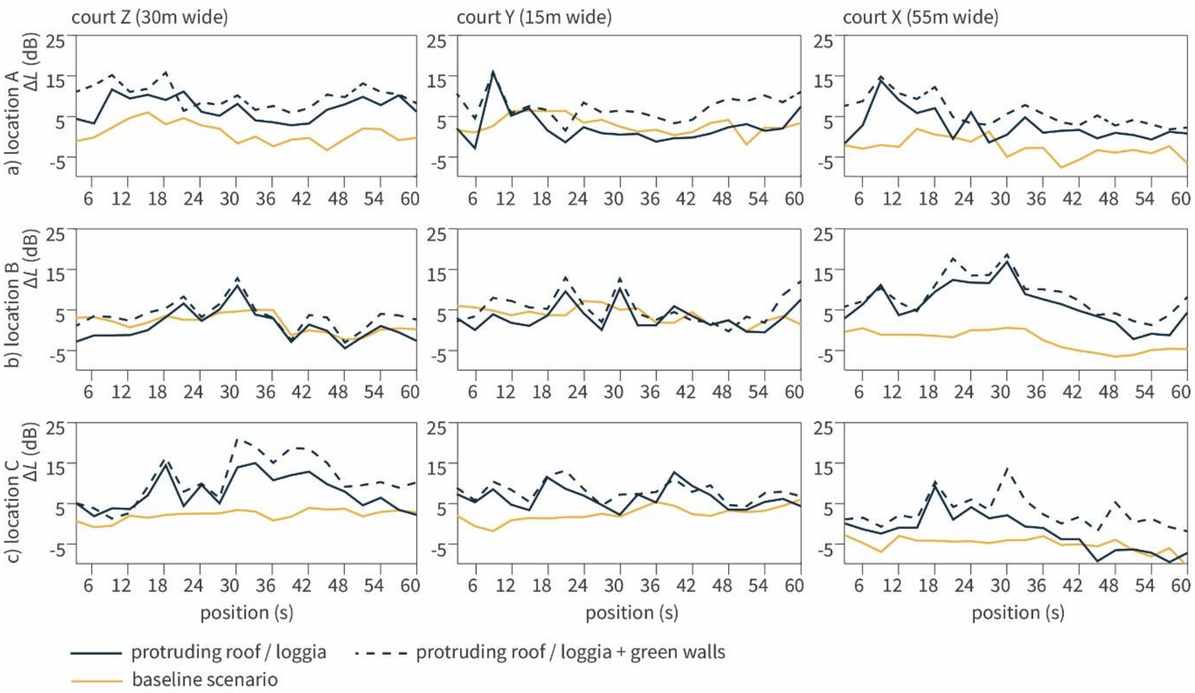

Figure 57 Differences between shielded and exposed building sides (ΔL) for the baseline scenarios with protruding roofs and bays, and the baseline with protruding roofs, bays and green walls. Results are plotted for each aircraft position and only for the 250Hz octave band.

Table 24 Results for the ΔL_{eq} between the baseline scenarios and the interventions (I). P refers to scenarios with protruding roofs and bays, G refers to green walls. Results are given per octave band and for each canyon width (C) (X, Y, Z), and per location (A, B, C), given in dB.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	P	3	-6	1	2	-1	3	5	-1	5	10	1	5	12	4	7
	PG	6	-4	2	6	-1	5	9	1	6	14	5	8	16	5	8
Y	P	-3	-6	-3	-2	-3	3	-2	-1	3	0	3	2	3	4	2
	PG	-4	-4	-1	-1	0	4	3	1	5	4	5	4	8	8	5
X	P	1	1	-2	3	5	0	4	9	1	8	10	2	11	16	4
	PG	2	2	2	5	7	4	9	11	7	13	15	8	18	19	10

The third analysis focused on the noise abating effect of variants comprising overhanging roofs, loggias and/or green walls. Table 23 and Table 24 and Figure 57 show the results for the ΔL_{max} and ΔL_{eq} respectively. The tables show clear differences between the different street canyons, i.e. the added noise abating effect increases with the width of the canyon. These differences are most pronounced for OBs <250Hz. In the best case, i.e. a canyon width of 55m, the added sound attenuation varies between 5dB a6 63Hz to >25dB for 1000Hz. The differences between the canyons are caused by 'trapped' sound, as is also the case for tall buildings. This means that reflected sound is trapped in the canyon as the overhanging roof narrows the opening of the canyon. Waves reflected downward travel via the walls to the ground surface and but will again reflect towards the ground surface via the overhanging roof. This effect is strongest for lower frequencies, because the surface materials hardly absorb low frequency sound. Hence the sound levels increase compared to the baseline scenarios. For wider canyons, the effects of reflections against opposite walls are weaker, and the overhanging roof will abate sound near the shielded facade because it increases the propagation path and scatters the sound around its edges.

Table 13 and Table 14 present the results of a series of Kruskal-Wallis tests with Bonferroni post hoc corrections. Table 25 shows that, in terms of the difference between exposed and shielded positions, the interventions induce a significant effect for most frequencies and canyon typologies. However, the effects were stronger for wide canyons, and OBs =>250Hz.

Table 26 shows that the sound abating effect of the interventions was even stronger for the shielded positions. Again, the interventions yielded a stronger sound reducing effect for the widest canyon. For the narrowest canyon, the tests revealed no significant effects of the interventions for 63Hz for location A and C. This is attributed to a sound 'trapping' effect induced by the overhanging roof, which basically narrows the opening of the canyon. The two tables show that, for wide canyon typologies, overhanging roofs, loggias and green walls have a stronger aircraft noise abating effect than the baseline scenarios for all OBs and for all the locations analysed.

Table 25 Results for Kruskal-Wallis and Bonferroni post hoc tests per octave band for each canyon width and location (A, B, C). B refers to baseline scenario(s), P refers to scenarios with protruding roofs and bays, G refers to green walls.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	X^2	*10.738*	13.911	5.570	21.404	3.059	19.200	39.471	7.606	30.807	41.906	23.398	32.461	41.189	26.164	32.292
	p	.005	.001	.062	>.001	.217	>.001	>.001	.022	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	B-P	.023	>.001		.020		.002	>.001		>.001	>.001		>.001	>.001	.001	>.001
	B-PG	.001	.012		>.001		>.001	>.001		>.001	>.001	>.001	>.001	>.001	>.001	>.001
	P-PG				.021			.042	.006			.001				
Y	X^2	5.670	21.358	.836	.835	8.688	17.104	23.272	4.706	33.007	32.013	22.057	16.451	23.516	37.900	20.169
	p	.059	>.001	.658	.659	.013	>.001	>.001	.095	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	B-P		>.001			.003	.004			>.001		.033	.043		.002	.021
	B-PG		>.001				>.001	>.001		>.001	>.001	>.001	>.001	>.001	>.001	>.001
	P-PG							>.001			>.001	.010		>.001	.008	.028
X	X^2	3.720	.727	5.857	17.773	15.199	20.012	37.716	35.576	31.376	40.015	42.529	34.227	37.644	41.443	33.148
	p	.156	.695	.053	>.001	.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	B-P				.001	.002	.020	.001	>.001	.024	>.001	>.001		>.001	>.001	.030
	B-PG				>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	P-PG						.031	.017		.001		.046	>.001			>.001

Table 26 Results for Kruskal-Wallis and Bonferroni post hoc tests per octave band for each canyon width and location (A, B, C). B refers to baseline scenario(s), P refers to scenarios with protruding roofs and bays, G refers to green walls.

C	I	octave band														
		63 Hz			125 Hz			250 Hz			500 Hz			1000 Hz		
		Location			Location			Location			Location			Location		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Z	X^2	*31.044*	16.240	17.272	36.836	2.869	31.807	38.312	9.541	33.263	34.556	18.745	34.556	29.568	20.550	28.223
	p	>.001	>.001	>.001	>.001	.238	>.001	>.001	.008	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	B-P	>.001	>.001	>.001	>.001		>.001	>.001		>.001	>.001		>.001	.001	.008	.002
	B-PG	>.001	.019	>.001	>.001		>.001	>.001	.012	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	P-PG				.043			.020	.005			.003				
Y	X^2	6.387	16.968	1.835	11.008	9.980	27.095	19.873	7.133	27.402	17.336	20.732	19.287	14.934	25.409	13.460
	p	.041	>.001	.400	.004	.007	>.001	>.001	.028	>.001	>.001	>.001	>.001	.001	>.001	.001
	B-P		>.001		.042	.040	>.001			.001			.033		.038	
	B-PG		.014		.001		>.001	>.001		>.001	>.001	>.001	>.001	>.001	>.001	>.001
	P-PG	.012				.002		.001	.011		.004	.004		.018	.003	.016
X	X^2	16.385	8.298	11.016	30.660	41.892	28.931	38.295	43.987	38.430	36.528	48.602	34.576	31.844	48.709	34.711
	p	>.001	.016	.004	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	B-P				>.001	>.001	.028	>.001	>.001	.017	>.001	>.001		.003	>.001	.048
	B-PG	>.001	.005	.030	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001	>.001
	P-PG	.019		.001		.038	.002	.011	.031	>.001	.017	.002	>.001	.008	.002	>.001

7.4.5. Street orientation

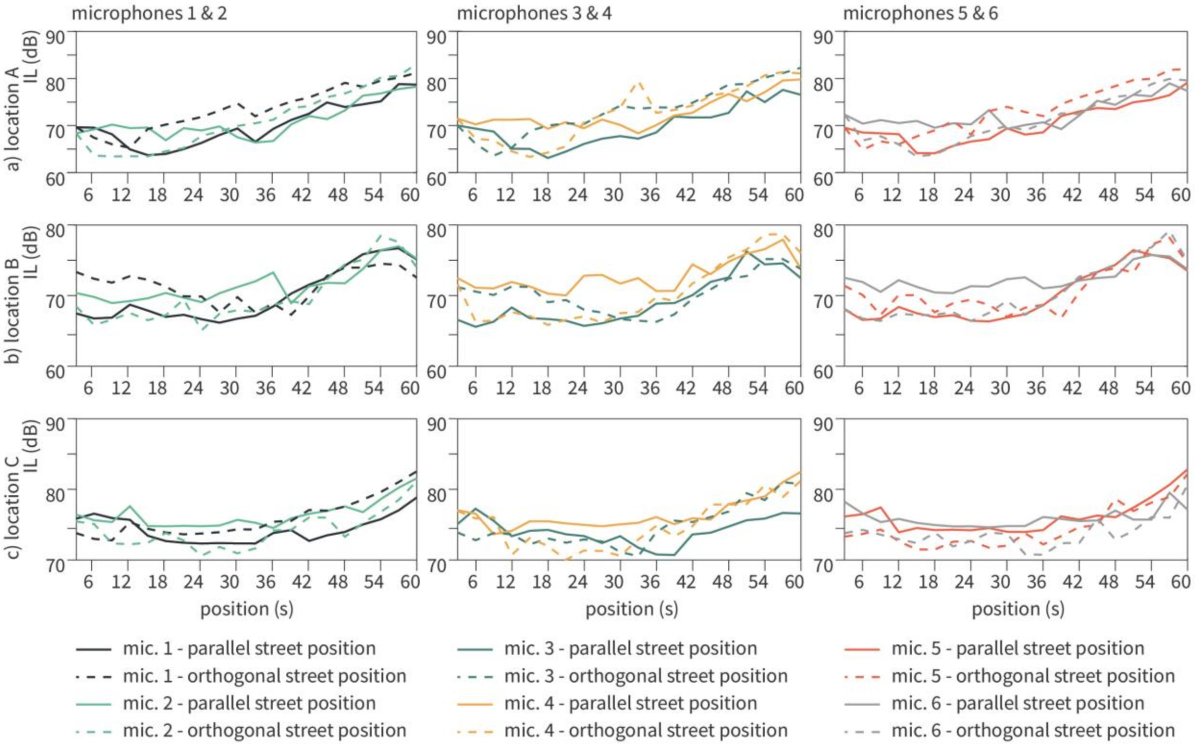

Figure 58 Insertion Loss per microphone for pairs of shielded and exposed building sides for the baseline scenarios (solid lines), and when the baseline scenarios are rotated by 90° around its axis (dashed lines) (see Figure 51). Results are plotted for each aircraft position and only for the 250Hz octave band.

Figure 58 shows the results per microphone for streets either parallel or orthogonal to the direction of the flight path for the 250Hz OB. For configurations rotated by 90°, the difference between the shielded and exposed sides seemingly disappears or reverses. Instead, the previously exposed positions are often quieter than the previously shielded positions. This effect is most visible for microphones 1 and 2. The figures suggest that, for the overall sound abatement, the position of the source in relation to the receiver is more important than whether the buildings are orientated in parallel or orthogonally to the flight path. However, if microphones are positioned in orthogonal streets, they will be exposed to direct sound waves at some point during the flight directory. Figure 58 shows that the minimum insertion loss is similar for microphones positioned around the same building. This means that the peak exposure levels will be comparable at both sides of orthogonal streets. Thus, although the average sound level may be lower at one side within such streets, the street orientation does not affect the maximum exposure level. Since both the average and peak exposure levels influence the perception of annoyance, it would better to aim for a street design that differentiates the exposure levels and thus protects certain places within the street from direct exposure to aircraft noise.

7.4.6. Aircraft noise abating potential around the case study sites

For the final part of the study, it was evaluated what the numerical results would mean for the reduction of aircraft noise at the case study locations. In other words, to what extent is the audibility of aircraft reduced, and for which tonal components. Only the variants that yielded a significant noise reducing effect near the shielded facades were considered. The study focused on the mean maximum sound level during aircraft flyovers for three exposed positions (for microphones A-1, B-1 and C-4), and the average ambient sound levels. In this study, the ambient sound levels as measured behind buildings, i.e. shielded from road traffic noise, were considered as the minimum thresholds for the sound level near shielded facades. As the results of the numerical study gave negative results for tilted facades, only the impact of tall buildings and overhanging roofs, loggias and green walls were studied. In addition, the sound abating potential was only calculated for the widest and most narrow canyon typologies.

Table 27 shows the results of the design variants for a narrow and a wide canyon. The table shows that, for aircraft noise reduction, increasing the height is a more effective intervention than overhanging roofs and loggias. Moreover, having taller buildings in narrow streets results in greater noise reduction than having taller buildings in wide streets, at least for location A and C. The results for location B suggest that the altitude of the aircraft reduces this difference. Compared to location A, the mean flight path is ≈200m higher for location B. Although the horizontal distance to the locations' ground track is comparable, this means that the angle at which sound waves hit the buildings will be steeper. This diminishes the number of reflections between the walls and thus negates the benefits of a narrow canyon. This same effect was also found for overhanging roofs and loggias. Taller buildings, when combined with absorbing green walls, increase the number of reflections between walls before the reflected sound reaches the microphone. However, overhanging roofs, when combined with a narrow canyon, trap the sound between the buildings. This negates the added noise abating effect of the protruding roofs. The results show that, for certain frequencies, the combination of a narrow street and tall buildings reduces the aircraft noise to below the ambient sound levels for location A and C. For location C, this is also the case for a wide canyon profile in combination with tall buildings and vegetation, or with overhanging roofs, loggias and vegetation. Therefore, the tonal components characteristic of aircraft noise might be masked by other ambient sounds. This might reduce the saliency of the aircraft noise and/or make it more difficult for receivers to identify the sound as aircraft noise.

Table 27 Prospect of sound abatement, i.e. the reduction of peak levels, for two design alternatives, calculated for three OB for each of the case study locations. BL stands for baseline scenario, H2G refers to a building height of 12m and green walls. ORLG refers to overhanging roofs, loggias and green walls. [a] refers to results that were not significantly different from the baseline scenario, * refers to results attenuating the sound below the ambient sound level.

Location	Peak and ambient sound levels	Canyon density	Intervention	octave band		
				63Hz	125Hz	500Hz
A	Mean peak sound level during an aircraft flyover for microphone A-1			63dB	65dB	68dB
	Average ambient sound level for microphone A-2			45dB	45dB	44dB
		Wide	BL	54dB	60dB	63dB
		Narrow	BL	54dB	55dB	60dB
		Wide	H2G	48dB	53dB	50dB
			ORLG	49dB	53dB	47dB
		Narrow	H2G	46dB[a]	45dB*	44dB*
			ORLG	48dB[a]	46dB	44dB*
B	Mean peak sound level during an aircraft flyover for microphone B-1			63dB	64dB	65dB
	Average ambient sound level for microphone B-2			46dB	44dB	50dB
		Wide	BL	53dB	58dB	59dB
		Narrow	BL	53dB	54dB	57dB
		Wide	H2G	46dB*	45dB	50dB*
			ORLG	46dB*	51dB[a]	50dB
		Narrow	H2G	47dB[a]	52dB[a]	52dB
			ORLG	50dB	47dB[a]	52dB
C	Mean peak sound level during an aircraft flyover for microphone C-4			55dB	53dB	54dB
	Average ambient sound level for microphone C-5			42dB	38dB	37dB
		Wide	BL	50dB	48dB	50dB
		Narrow	BL	49dB	48dB	51dB
		Wide	H2G	42dB*	38dB*	37dB*
			ORLG	42dB*	38dB*	37dB*
		Narrow	H2G	42dB*	38dB*	38dB*
			ORLG	46dB[a]	41dB	40dB

7.5. Discussion and conclusions[7]

This chapter demonstrated the influence of architectural design variants on the abatement of aircraft noise. The study focused on the following two objectives:

3. To examine the aircraft noise abating potential of different architectural design variables for three canyon-width profiles.
4. To estimate the sound reduction induced by different architectural design variables at three sites near Amsterdam Airport Schiphol.

Firstly, the acoustic impact of five architectural design variables, 1) building height, 2) facade orientation, 3) roofs and loggias, 4) surface materials and 5) the orientation of the street, were calculated and compared to a baseline scenario for three different canyon widths. The study used an

[7] The same structure was used as in chapter 5, i.e. the discussion and conclusions are combined.

existing numerical model and assumed a weather situation corresponding to a typical summer day in Northwest Europe.

The results show that green walls only yielded a significant noise reducing effect when combined with an increased building height or with overhanging roofs and loggias. Tilting the facade only reduced the sound levels near exposed facades, but did not further reduce the sound levels near shielded facades. Moreover, for most frequencies, the effects of tilted facades, compared to the baseline scenarios, were not significant. However, the sound levels were significantly lower if the building height was increased, or if overhanging roofs and loggias were added to the baseline variants. The extra reduction of the peak exposure level, compared to the baseline scenario, is estimated to vary between 5dB (63Hz) and >20dB (500Hz) for a height increase of 12m with green walls, and between 5dB (63Hz) and 15dB (500Hz) for overhanging roofs, loggias and green walls. However, for locations relatively close to the flight path (<1000m), and with relatively high flight altitudes (>1600m), the results show that it is better not to opt for narrow canyons. Since the combination of tall walls and narrow canyons could trap the sound, the sound level near shielded facades can be substantially higher in narrow canyons, compared to the sound levels in wider streets with smaller buildings. Mounting absorbing materials can partially solve this problem, but only when frequencies are >250Hz. The street orientation, i.e. perpendicular or orthogonal to the flight path, affects which microphones are directly exposed to aircraft noise and which are not. If the direction of the streets is orthogonal to the flight path, the differences between formerly exposed and shielded positions in a canyon will vanish. Although the average sound exposure levels may still vary within the canyon, the peak levels will become the same near both exposed and shielded facades. In relation to previous research on the perception of aircraft noise annoyance, this is not ideal, as the peak levels also influence the level of annoyance.

The application of the results at the case study locations suggests that certain tonal components of the aircraft noise may be masked by the ambient sound. For the location at greatest distance from the flight path, the analysis suggests that taller buildings with green walls could even mute the aircraft completely.

However, in practice, the results might deviate from the numerical predictions due to the limitations of the model. A comparison between the numerical model and in-situ measurements showed that the model underestimated the sound abatement of buildings in some cases, especially for higher frequencies. Location A lends itself the best for a comparison between the numerical results and measurements, as one of the existing buildings at this location towers 21m above the surrounding two microphones, and so is comparable to the tallest building in the variant study. Comparing the measurements and the calculations for the 250Hz OB showed that the model predicts a slightly lower sound reduction than the average reduction as measured based on 53 flights. This could mean that the average noise reduction results can be greater in practice than predicted in this study. However, factors such as the wind speed, wind direction, temperature, time of day, aircraft type and the flight path will also have a significant effect on the exact sound propagation around buildings. This means that the noise reducing potential of a building will vary, but the results in this study are representative of the average reduction that can be expected.

The results presented in this study show the importance of urban and architectural design near airports. Good and careful design can contribute to a reduction of the sound exposure and consequent noise annoyance in such areas. However, more research is needed to understand how the noise reduction around buildings varies for different weather types and flight paths around the buildings.

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8. Improving the soundscape quality of urban areas exposed to aircraft noise by adding moving water and vegetation[8]

8.1. Abstract

Research shows that the sight of trees and the sound of moving water improve the soundscape quality of outdoor spaces exposed to road traffic noise. Effects are attributed to non-energetic masking, visual attentional distortion and congruence between sight and hearing. However, there is no literature on such effects for aircraft noise. Aircraft noise varies from other traffic sources, i.e. in terms temporal variability, duration and spectral composition, complicating the application of findings without further research. In a VR experiment reported in this article, participants were asked to rate scenarios with different sound levels of flyovers, urban typologies, vegetation and/ or water features. The results showed a significant improvement of the soundscape quality when 1) vegetation and 2) moving water were present, and especially when 3) vegetation and moving water were presented simultaneously, especially for residential areas in terms of the relative change. Moving water also reduced the saliency of aircraft flyovers significantly, changing the constellation of fore- and background sounds. Moving water raised the perceived audibility of the most dominant sound source too, which could be attributed to non-energetic masking effects. Our findings indicate that soundscape strategies can complement noise abatement in areas prone to aircraft noise.

8.2. Introduction[9]

Urban areas close to airports are exposed to aircraft noise which can result in annoyance and health complaints [1,2] . Over the last decades, a variety of interventions have been developed to limit sound exposure from road, rail and air traffic. The acoustic solutions range from quieter engines and airframes [3] to noise barriers [4], the design of urban blocks [5] and building insulation schemes [6]. The effectiveness of these measures varies per case and per sound source, but mitigations like barriers and material properties become less effective when sound comes from above compared to sources close to the ground [7,8]. Because studies have shown that noise annoyance is also influenced by non-acoustic factors, e.g. noise sensitivity, attitudes, stress, trust in the authorities, fear, coping, time of the day, activities undertaken, perception of the source [9,10], and by personality traits [11,12], noise studies focus increasingly on the interaction between acoustic stimuli, receiver and context. In this respect, various studies point to the positive effects of natural scenes [13] and the audio-visual interplay between moving water sounds and vegetation [14,15], and the acoustic masking effect on the auditory appraisal of places

[8] This chapter was co-authored by Merve Karacaoglu (second author), Kim White (third author), Jian Kang (fourth author) and Koen Steemers (fifth author) and published in the Journal of the Acoustical Society of America. See appendix A for more information about the chapter and publication.
[9] This section is identical to the 3.2.2. and 3.2.3. with the literature sections used for the introduction of the publication.

exposed to road or railway noise [16,17]. This suggests traffic sounds are perceived as less annoying when water sounds are audible and foliage or vegetation are visible. However, for aircraft noise, these effects have not yet been explored. Aircraft noise differs from road or rail traffic in terms of spectral composition and the duration of a sound event [18], position towards an observer, salience and attitude [19,20]. Because of these differences between aircraft and other traffic modalities, the question rises whether the presence of water and vegetation can equally improve the soundscape perception in areas exposed to aircraft noise. Sounds from moving water vary in temporal variability, loudness and sharpness, and can be artificial or natural [21,22]. A few listening-only studies reported sea waves as the most pleasantly rated water variety [15,23], but sea sound is hard to implement in urban settings when designing for places that are not close to the coast. Water sounds do not improve the soundscape quality in all situations though [21], and therefore the right source must be carefully designed and selected during implementation. For example, it was found that waterfalls or water features generating a relatively constant and low frequency sound were rated as less pleasant than babbling streams, which have a higher temporal variability [14,21]. Galbrun and Ali [14] showed that, except for waterfalls with a high flow rate which generate higher levels of low frequency sound, the frequency response of water features and traffic sounds do not match. This means that the most preferred water features can mask traffic sounds in more ways than only obscuring the sound signal energetically. Sound masking techniques can be divided in two groups; 1) energetic, and 2) non-energetic or informational masking [24 refering to e.g. ,25]. Energetic masking makes a target sound inaudible by adding sound with a similar spectral and power domain. In the second form of masking, the masking sound is (partially) different from the target sound, but creates uncertainty about the origin and meaning of the sound [24,26]. Therefore, it becomes harder to distinguish the target and masker sounds, increasing the audibility threshold of the individual sounds [27]. In urban contexts, masking is linked to the source prominence and ranking between fore- and background sounds, which make the soundscape of an area [28]. In other words, the saliency of sounds can be influenced by enhancing other sounds. Literature showed that adding moving water changed what people saw as the most prominent source for a soundscape, seen as a form of non-energetic masking by the authors [29]. Water can mask traffic noise energetically, but only when the sound spectrum and temporal variance of the two (or more) sources coincide[14,22]. Galbrun and Ali[13] concluded that the frequency spectral components in road traffic make even the most preferred water varieties unsuitable for masking traffic noise energetically. Alternatively, studies suggest that added water can increase the auditory appraisal of road traffic noise by informational masking or distraction [29,30]. The sound level and spectral composition of added water features do not have to be equal to the traffic noise, but increase the soundscape quality when the water sound level is up to 3 dB(A) lower than the noise level of the traffic noise [14,30]. A careful design of water features in public places could therefore improve the soundscape quality of urban environments contaminated with mechanical sounds.

Studies on the effects of vegetation on sound appraisal range from research on the impact of landscapes and surroundings [31,32], to the role of trees and vegetation on walls [13], fences and (noise) barriers [33]. Traditionally, projections and images combined with headphones or speakers were used, whereas now integral technologies like virtual reality (VR) have become more common [16,34]. Results from previous studies stress the importance of congruence between expectations and soundscape [31,35] and the positive effects of vegetation and natural visual cues in urban areas [31]. Also, it was found that the perception of noisiness decreases when a source remains partly visible through the greening [33]. More recently, studies have focused on the impact of green walls and trees in urban settings outdoors [16,30], immersing participants in urban scenes by using projections or, more recently, virtual reality [16,36]. One finding was that vegetation, mainly in the form of trees, improved sound appraisal in an urban setting and scored better compared to other forms of vegetation like wall greening or shrubs [30]. Similar effects were found in a Belgian study where scenarios containing vegetation mounted on a fence over a motorway were most effective in improving the quality of the soundscape [37]. More importantly, in-situ studies show similar positive effects of visible green. In two separate studies, one in Belgium [38] and one in Hong-Kong [32], the sight of vegetation from within a dwelling decreased the level of self-reported noise annoyance by residents exposed to traffic noise. On a larger urban scale, vegetation and access to green areas (e.g. parks or nature) contribute to a lower annoyance rating from traffic noise [12,39]. This is not only attributed to the restorative character of green areas, but also to the aesthetic qualities of vegetation [40–42]. Van Renterghem [13] showed that visible vegetation restores attenuation and provides stress relief, which reduces the negative effects of noise exposure. The psycho-acoustic effect of vegetation is estimated as the equivalent of a noise reduction of 10dB(A), and the effect is larger for higher sound exposure levels [13].

So, literature indicates the potential of moving water and visual vegetation to improve the perception of soundscapes. The question was, however, if moving water and the visibility of vegetation would improve the soundscape quality of civic areas exposed to aircraft noise. To the best of our knowledge, no information on this currently exists. Based on literature four hypotheses were formulated:

1. Visible vegetation in the form of trees is expected to improve the soundscape quality.
2. Moving water (water jets) is expected to improve the soundscape quality.
3. Visible vegetation and moving water combined would improve the soundscape quality even more than both interventions separately.
4. Moving water (water jets) diminishes the saliency and dominancy of aircraft flyovers.

This paper presents the results of a study examining these hypotheses.

8.3. Methods

8.3.1. Participants

Forty-one participants (32 females and 9 males, mean age 21.5 year, SD 2.5 year) took part in the experiment in a sound-attenuated laboratory room at the Vrije Universiteit Amsterdam. Data from two female participants were discarded after it turned out that nearly all their answers were marked as outliers when analysing the distribution of the data in Tukey boxplots. The research was carried out in Dutch with Dutch speaking participants only, all in good health and with good self-reported hearing. Participants were asked for written consent and the study was conducted in accordance with the norms of the Helsinki declaration [43]. This study was approved by the Psychology Ethics Committee of the University of Cambridge.

8.3.2. Materials

8.3.2.1. Conditions

The study design was built upon four independent variables with two levels each: 1) urbanity (residential or commercial area), 2) aircraft flyovers (sound levels: 60 or 70 dB(A)), 3) vegetation (present or not present), 4) water features (fountain; present or not present). The combination of these four variables led to a total of sixteen conditions. Four samples without aircraft noise were added to move attention away from the flyovers and to ensure that participants would not focus on the aircraft alone. All scenarios were repeated twice, leading to a total of 40 scenarios. Participants were asked to fill out a questionnaire on a laptop after each scenario. Each of these variables is introduced in more detail below.

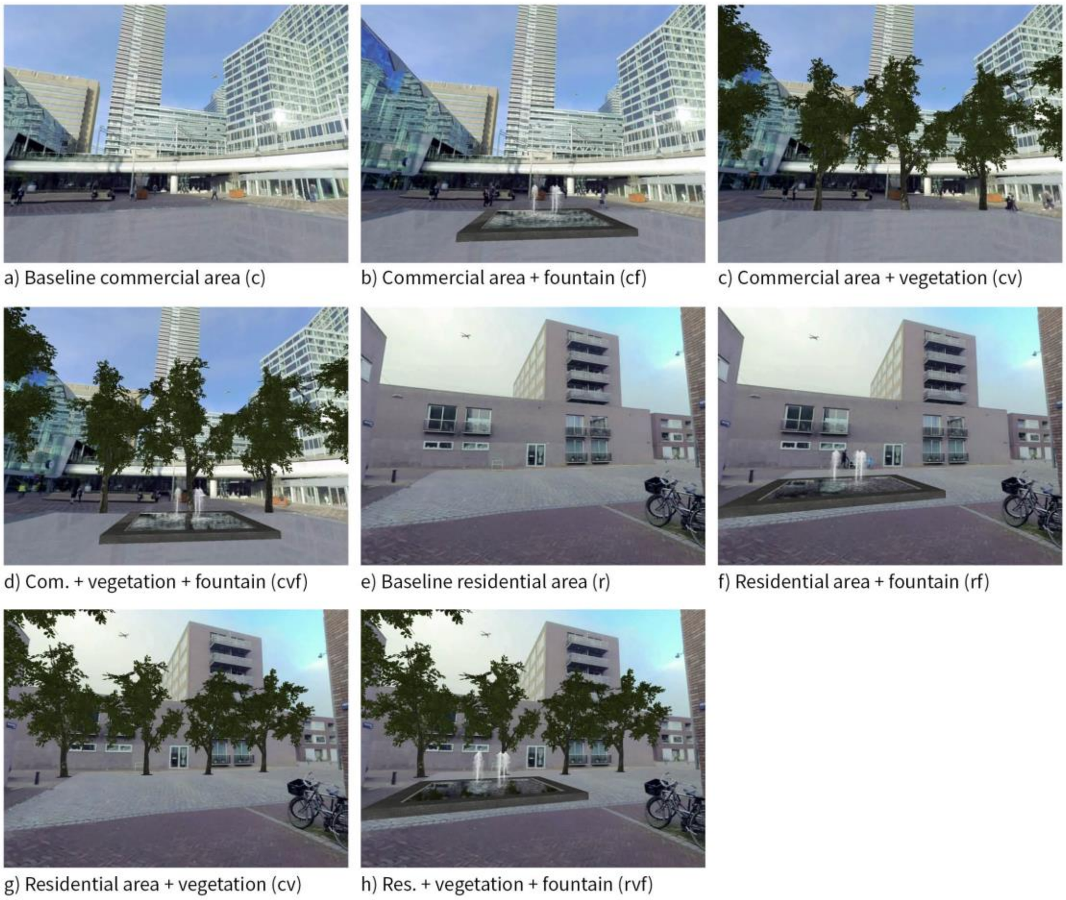

Figure 59 Scenarios for commercial and residential areas which were combined with flyovers at 60 and 70 LAmax.

8.3.2.2. Urbanity

The baseline scenarios were filmed at two locations in the Netherlands, representing a commercial and a residential area. The commercial area (Figure 59, a-d) was a square located next to the central railway station in the city of Den Haag surrounded by shiny glass-clad high-rise buildings. Pedestrians, cyclists, trams and vans rendered the scene vivid and dynamic. Footage for the residential site was shot in Amsterdam (Zeeburg district) (Figure 59, e-h) in a relative densely built-up urban area (built in the 2000s) with little human activity, albeit close to a playground (resulting in children's voices in the background). The requirement for both sites was that no vegetation would be visible from the position of the camera. Both sites were recorded with a 360° camera formed by 8 GoPro Black edition (resolution 1440 p / 60 fps). The cameras were mounted on a sphere on top of a tripod (1.7 m high), to simulate eye-level. The individual frames were stitched together using Kolor autopano Video (KaV) software. Any visible vegetation, visually distracting pavement textures and street and railway signs were removed from the video, using Adobe Photoshop CC 2017 and Adobe Pro CC 2017. From the footage, clips with a duration of 55 seconds were cut and used as baseline scenarios, one clip for each location. The ambient sound was recorded with mono (Brüel & Kjæl 4189/2671) and binaural microphones (four-channel H2n). Recordings from the mono microphone were used to calibrate and set the sound level for the binaural samples. The microphones were placed directly underneath the sphere with the cameras. The maximum sound level in the excerpts was kept below 60 dB(A) by muffling tonal pitches surpassing 60 dB(A) using Audacity (version 2.1.3). Only in few cases, sharp tonal pitches from a passing tram in the commercial area were modified, as the researchers were afraid that a sharp sound from the wheels would be too distractive.

8.3.2.3. Aircraft flyover

For the aircraft flyover, a sample of a regular descending Airbus 330 aircraft (A330) at 2000 ft (≈610 m). from a previous study [44] was used and calibrated for two L_{Amax} values (60 dB(A) and 70 dB(A)) (see Figure 60). The spectral composition, size, (visual) position and altitude of these flyovers used in this study were identical, in order not to introduce any extra variables. The flyover was clearly visible from the default direction of view.

The flights were modelled using the Netherlands Aerospace Centre's (NLR) Virtual Community Noise Simulator (VCNS) that generates a real-time virtual environment in which audio and visual signals are adjusted and synchronized with a head-mounted display and head-tracking headphones [44,45]. The sound signals were binaural and based on real-time audio rendering, creating an immersive stereo sound environment around the participant. Subjects could rotate 360° degrees around the axis of the camera position but could not walk through the scenes. Studies show that a combination of videos and animations in the VCNS gives a realistic impression of an aircraft flyover [46,47].

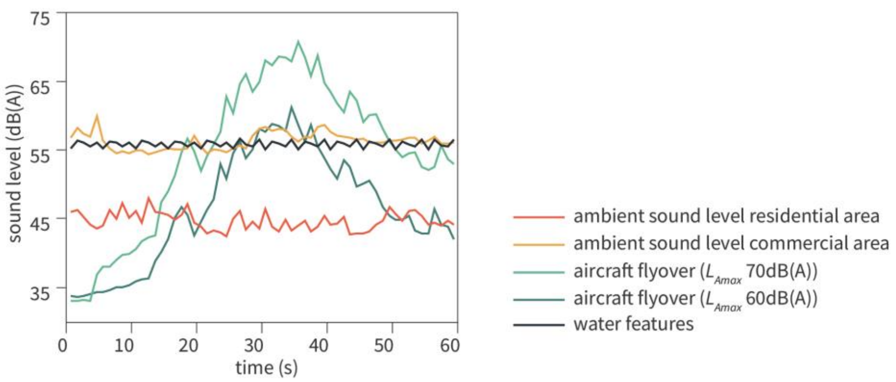

Figure 60 *Sound level (in dB(A)) for sounds presented during the experiment: orange = aircraft flyover (L_{Amax} 70 dB(A)), dark blue = fountain, grey = ambient sounds commercial area, light blue = aircraft flyover (L_{Amax} 60 dB(A)), yellow = ambient sounds residential area.*

8.3.2.4. Vegetation

Animations of birch trees were selected from a default library for Unity props and integrated with the videos. The appearance of the props was further adapted and transformed to match the videos as realistically as possible. Unity 3D game engine (version 5.4.1f1) was used to merge animation, flyovers and videos. The trees were placed in a circle around the stationary position of the camera, creating a visually permeable green canopy surrounding the participant. The trees (vegetation) covered an average surface of around 20 percent of the default view from eye-level based on analysis in Adobe Photoshop CS6.

8.3.2.5. Water (fountain)

The water variable comprised three fountain jets in the middle of a small rectangular pond, creating both a visual and acoustic effect. The visuals were selected from (default) Unity animated props while a binaural recording, derived from a study comparing various fountains for auditory quality [21], was used for the acoustic component. The sound sample was rated as second-best in the soundscape pleasantness assessments by Rådsten-Ekman [21], and represents a fountain formed by multiple jets with water falling down on water (pond or basin). The selected animation selected was carefully matched with the image of the fountain in the corresponding literature [21]. The fountain sound is characterized by its low variability and constant sound volume, which was calibrated at 57 L_{Amax} like in the study by Rådsten-Ekman et al. [21]. The water sound was approximately 3 dB(A) lower than the peak level of the quietest flyover (i.e., 60 dB(A)) in keeping with recommended settings for sound masking in relation to ambient noise in urban areas[48].

8.3.3. Apparatus

The scenarios were presented to participants using Unity 3D game engine (version 5.4.1f1) on an Intel i5 6600 CPU with a Nvidia GTX-970 graphic card and head-mounted displays (HMD, Oculus Rift CV1, refresh rate 90 Hz) and headphones (Bose QC 25). The headphones were calibrated with a dummy with two microphones at the position of the ears. The sound of the fountain was played, and the headphones and computer were adjusted to the right sound level.

8.3.4. Questionnaire

Because there are no standardized questionnaires for soundscape research (see e.g. [16,34,49,50]), let alone questionnaires for soundscape research using VR, a post-ante evaluation of questions and questionnaire was carried out.

The questionnaire consisted of three parts, with each one using questions from separate studies. Part one was formed of questions used in studies following the so-called ‘Swedish Soundscape Quality Protocol’. Soundscape perception is measured on a quadrant scale with the opposites ‘pleasant versus unpleasant’ and ‘eventful versus uneventful’ on both axes. A study by Axelsson, Nilsson and Berglund [51] showed that these factors combined with ‘familiarity’ explain most variance of soundscape perception (50, 18, and 6% respectively). Because of the predictive power of the opposites ‘soundscape pleasantness versus unpleasantness’ and ‘soundscape eventfulness versus uneventfulness’ for the perception of soundscape quality, these factors are frequently used to measure soundscape quality [28,52]. Soundscape pleasantness is generally attributed to natural sounds while soundscape eventfulness relates to the descriptions of liveliness and ambiance (e.g. the level of human sounds)(see e.g. [29,51]). The second part was formed by questions used in soundscape VR-based studies. In these studies, the perception of the auditory and visual components is tested separately, as well as the overall holistic perception. The third part consisted of questions about auditory attention and saliency to examine (non-energetic) masking effects used in soundscape research. The questions were previously used in in-situ studies to identify masking effects, e.g. of a fountain [29], or to study auditory quality in relation to activity and context [53]. The questions were translated from English to Dutch using standardized terms from previous soundscape studies in the Dutch language and the translations were kept as close as possible to the original question [52].

8.3.4.1. Pilot questionnaire

The first part of the questionnaire asked participants to rate 1) the general quality of the scenario *('From a global point of view, how would you rate the environment that you just explored?'),* 2) the general quality from a visual perspective *('From a visual point of view, how would you rate the environment that you just explored?')* and 3) the general quality from an auditory perspective *('From an auditory point of view, how would you rate the environment that you just explored?')* (see [50]). The second part of the questionnaire consisted of two questions related to the 4) pleasantness *('To what extent did you perceive the surrounding sound environment as pleasant in the environment that you just explored?')* and 5) the eventfulness of the sound environment *('To what extent did you perceive the surrounding sound environment as eventful in the environment that you just explored?')* (see [51,52]). Participants could rate each question on a linear scale between 0 and 10 (interval 1), ranging from (0) *'very bad'* to (10) *'very good'* for question 1-3, *'unpleasant'* to *'pleasant'* for question 4, *'uneventful'* to *'eventful'* for question 5. In the third part, participants were asked to write down the most prominent sound source heard in each scenario (*Please name the sound source which you perceived as most prominent in the environment that you just explored*) and to what extent this source dominated the soundscape (*To what extent did you hear this sound in the environment just explored?*). The first question was an open question while the second question asked participants to rate between the extremes *'did not hear at all'* and *'dominated completely'* between *0* and *10* (interval 1).

8.3.4.2. Orthogonality of factors

Table 28 *results of repeated measures MANOVA Bonferroni post hoc tests*

	Question 2	Question 3	Question 4	Question 5
Question 1	$p = 1.000$	$p = 1.000$	$p = .162$	$p < .001$
Question 2		$p = 1.000$	$p = .248$	$p < .001$
Question 3			$p = 1.000$	$p < .001$
Question 4				$p = .011$

As the scenarios were presented twice, the mean score from the same two trials was calculated before analyses. Main effects and interactions between the conditions were studied by performing a Repeated Measures Multivariate Analysis of Variance (MANOVA) for the first five questions. In the MANOVA the orthogonality of the different factors tested per question was examined. Results showed that the first five questions were significantly different from each other ($F(4,190) = 10.855$, $p < 0.001$, $r = 0.23$), but a subsequent Bonferroni post-hoc test showed that only question 5 was significantly different from the other questions (see Table 28). This means that none of the metrics as asked in questions 1-4 (overall quality, overall visual quality, overall auditory quality and pleasantness) differed significantly from one another. This means that the composite of the four questions could be studied as a whole by adjusting the F-values or by including the factor 'question' as a between-subjects factor[54]. Consequently, if all four questions were to be taken together as one, the rigidity of the statistical test would increase, inflating the risk of a type II error. Based on these arguments, the decisions was made to disregard the first three questions and focus on the auditory pleasantness and eventfulness instead (i.e. question four and five), as the predictors of soundscape quality. Therefore, only questions 4-7 were used for further analysis.

8.3.5. Procedure

Upon arrival, participants signed the informed consent, after which they were led into a sound-attenuated room where the head-mounted display and headphones were fitted. To optimize immersion in the virtual scenes and to avoid a focus on auditive stimuli only, participants were asked to experience each scenario as if they were passing by this area and decided to pause for a moment. Also, they were told that the locations were situated in a metropolitan area (containing commercial and residential sites), wherein traffic (including cars, trams, trains and aircraft), people and amenities surrounded the scenes. Participants began the experiment with a practice session in which they passively experienced baseline scenarios from the two areas from a standing position. Once they were adjusted to the VR-setting, the actual experiment commenced with presentations of the conditions in random order, controlled by the experimenter present in the room. The total duration of the experiment varied between 90 and 120 minutes per candidate. Participants were allowed to take a small pause after each scenario without leaving the sound-attenuated room.

8.4. Results

8.4.1. Soundscape quality

For the data analyses, only results from scenarios containing aircraft flyovers were included. The results of these sixteen scenarios were analysed by means of a repeated measures ANOVA design for the two relevant questions for soundscape quality. The two predictors for soundscape quality, auditory pleasantness and eventfulness, are presented and discussed together. The results for the three interventions are presented one by one.

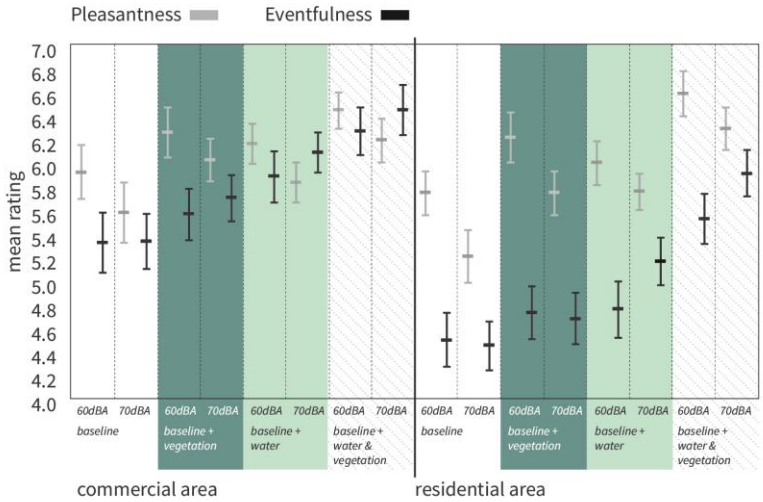

Figure 61 *Mean ratings and standard error of the mean (+/-SEM) for soundscape pleasantness and eventfulness ratings per scenario (see* **Figure 59***); split according to location (commercial area on the left-hand side, residential area on the right-hand side), and grouped per intervention (none, vegetation, water, vegetation and water combined).*

Table 29 *Percentage change of mean ratings of scenarios with vegetation, water, combination of water and vegetation compared to the baseline scenarios (water / vegetation absent, 60dB(A) and 70dB(A)) for soundscape pleasantness and eventfulness*

Change in %	Commercial area						Residential area					
	Vegetation		Water		Combined		Vegetation		Water		Combined	
L_{Amax} in dB(A)	60	70	60	70	60	70	60	70	60	70	60	70
Pleasant-ness	+5.6	+8.0	+6.9	+7.6	+11.7	+11.0	+8.3	+10.3	+4.5	+10.6	+14.7	+20.9
Eventful-ness	+4.6	+7.0	+10.6	+14.2	+17.8	+20.9	+5.1	+5.2	+5.7	+16.1	+22.8	+32.9

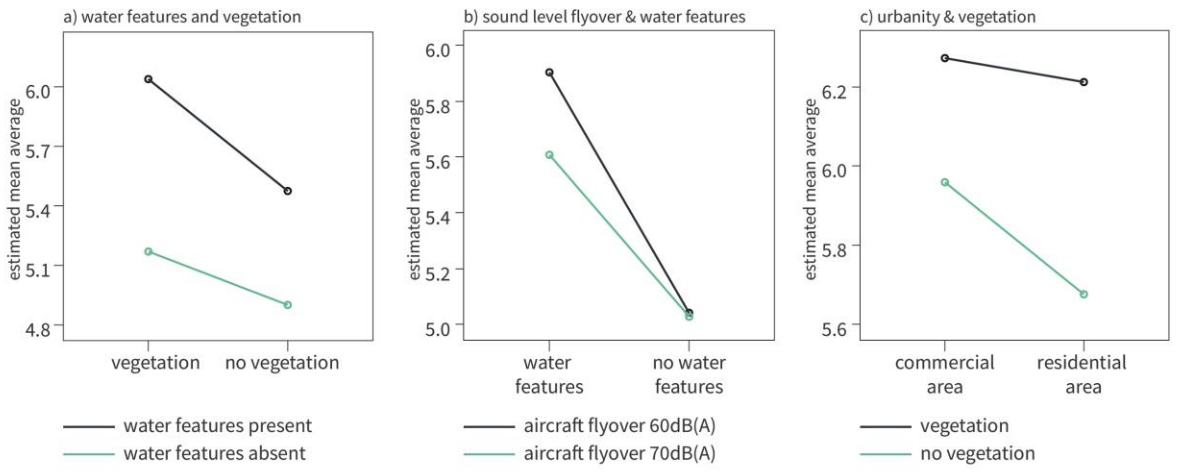

Figure 62 *Estimated marginal means for the interactions between a) eventfulness scores for water features and vegetation, b) eventfulness scores for the sound level of the aircraft flyover and water features and c) pleasantness scores for urbanity versus vegetation*

8.4.1.1. Vegetation

A main effect of vegetation was found for both predictors of soundscape quality (auditory pleasantness; ($F(1,38) = 52.54$, $p < 0.001$, $r = 0.76$), and eventfulness ($F(1,38) = 37.12$, $p < 0.001$, $r = 0.70$)). The results show that the presence of vegetation led to higher ratings for both indicators. The direction of the main effect is visible in Figure 61. The figure shows that the absolute change in scores was higher for the residential area compared to the commercial site. This effect can be also observed in Table 29, which represents the percentage of change in the ratings of scenarios with the interventions compared to the baseline scenarios. The mean ratings for soundscape pleasantness increased by approximately 7% for the commercial area and 9% for the residential area when vegetation was present. In the same way, eventfulness ratings increased by 6% and 5% for the commercial and residential areas respectively when vegetation was visible. An interaction between urbanity and vegetation was found ($F(1,38) = 4.64$, $p = 0.038$, $r = 0.33$) for soundscape pleasantness, see Figure 62. The graph shows that the soundscape was perceived as more pleasant in both areas where vegetation was present. However, the difference between the absence and presence of vegetation on the soundscape pleasantness was greater in the residential areas than in the commercial area. This suggests that vegetation as a strategy to improve the soundscape pleasantness is especially effective around dwellings. The results show that the presence of vegetation improved both the soundscape pleasantness and eventfulness compared to the baseline scenarios, with larger improvement observed for the scenarios containing the loudest aircraft flyover (70 dB(A)) and for the residential area.

8.4.1.2. Moving water

As with vegetation, the presence of water features had a positive effect on both the pleasantness and eventfulness ratings of the soundscape. The analyses showed that water was a main effect for both soundscape quality predictors (auditory pleasantness; (*$F(1,38) = 4.57$, $p = 0.039$, $r = 0.33$*), and eventfulness; (*$F(1,38) = 31.22$, $p = 0.001$, $r = 0.67$*). Table 29 and Figure 61 show that with the presence of moving water, mean ratings for the soundscape pleasantness increased by 7% in the commercial area and 8% for the residential area. For the soundscape eventfulness, mean ratings increased by 12% and 11% for the commercial and residential area respectively. Again, the percentage increase for scenarios with moving water compared to the basis scenarios was larger for 70dB(A) than for 60dB(A) flyovers. Moreover, the analysis revealed a significant interaction between water features and the sound level of the flyover (*$F(1,38) = 5.19$, $p = 0.028$, $r = 0.35$*) (see Figure 62b). When water features were absent, the sound level of the flyover did not affect the perceived eventfulness of the soundscape. However, when water features were present, the perceived eventfulness of the soundscape was higher for both flyovers, especially for the loudest flyover used in the experiment (70 dB(A) L_{Amax}). This could be related to the timespan during which the sound level of the fountains obscures that of the flyover (see Figure 60), which is shorter for a flyover with a L_{Amax} of 70 dB(A) (see e.g. [55,56]).

8.4.1.3. Combined effects

Compared to scenarios featuring either water features or vegetation, mean ratings for scenarios combining both interventions were higher for both soundscape pleasantness and eventfulness (see Figure 61 and Table 29). The scores for soundscape pleasantness increased by 11% and 18% for the commercial area and residential area respectively. For soundscape eventfulness, these scores increased by 19% and 28% for the commercial and residential areas compared to the baseline scenarios. The eventfulness ratings where higher for the 70dB(A) than for the 60dB(A) aircraft flyovers, especially for the residential area. The ANOVA revealed that the interaction between water and vegetation was only significant for soundscape eventfulness (*$F(1,38) = 6.49$, $p = 0.015$, $r = 0.38$*) (see Figure 62a). This interaction shows that although the vegetation did not change the sound signal, together with water features it made the participants perceive the soundscape as more eventful than could be accounted for by both factors individually. A similar interaction was not found for soundscape pleasantness.

8.4.2. Non-energetic masking effects

8.4.2.1. Source dominancy

For the last two questions participants were asked to write down the most prominent sound source heard per scenario and to rate the audibility of this sound source. The objective of these questions was to investigate the effect of vegetation and water on auditory masking. As each scenario was repeated twice, participants answered the question twice per scenario. Because the answers were categorical, it was not possible to average the results. Therefore, all answers were included in the data analyses meaning that 78 (39x2) possibilities per scenario were evaluated. In a few cases (20/1248; 1.6%), participants indicated two sound sources simultaneously. In these cases, only the first answer was selected for further analyses. This ensures that the combined size of data in the groups is similar before and after an intervention, which is required for the statistical analyses.

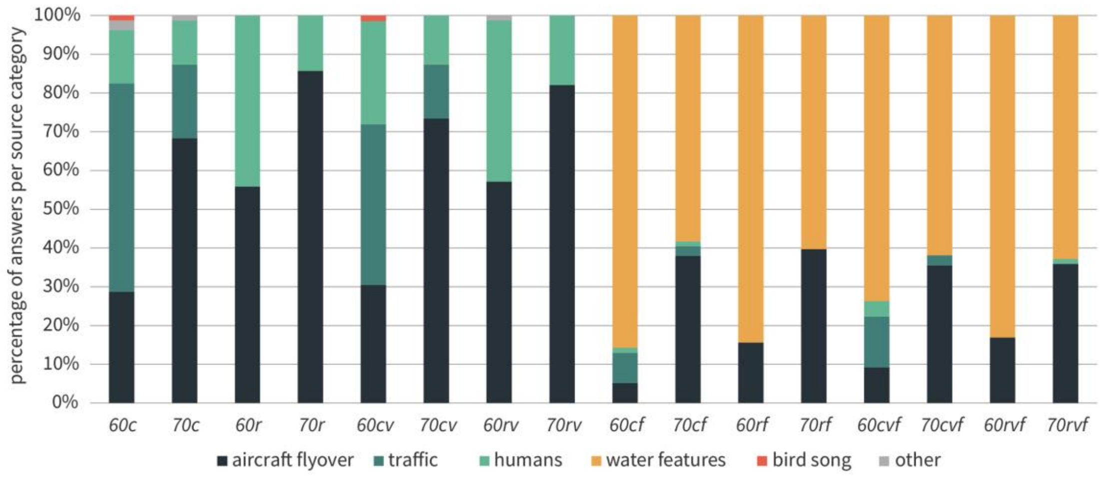

Figure 63 *Percentage of participant answers per scenario for the most prevalent sound, corresponding to one of the six sound source categories (aircraft, other traffic, human sounds, fountain, bird song, undefined)*

Figure 63 shows the distribution of the answers per scenario. The congruence between answers given between the first and second time scenarios were shown can also be seen. Answers from the open question were clustered into six categories; aircraft flyover *((faltering) aircraft, aircraft engines)*, traffic *(trams, cars, metro, trains, vans)*, humans *((playing) child(ren), footsteps, high heels, people talking, voices, people (passing))*, water features *(fountain(s), pond)*, natural sounds (*wind, bird song*), other *(rustling/sighing (i.e. suizen in Dutch))*. Participants reported answers falling in one of the last two categories in only 4 cases (0.3% of all answers given). The graph shows that for scenarios without any water features, aircraft, traffic and human sounds were most prominent in the soundscape. The graph suggests a shift from aircraft and traffic sounds to water features as the most prominent sound source when fountains were present.

It was also observed that there was no effect of vegetation on the most prominent sound source reported by participants, nor that vegetation and water combined led to different answers. These hypotheses were examined by applying three separate McNemar-Bowker tests to the data [57,see e.g. ,58]. This test was chosen because the data is categorical and not independent (repeated measures design), for which reason methods such as Pearson’s chi-square or multinomial logistic regression are not applicable. McNemar-Bowker tests for the symmetry of a contingency table while additional Bonferroni tests were used to study the direction of change [58]. This means that the symmetry between two groups is analyzed to study groups differ. To meet the assumption for the McNemar-Bowker test, the categories ‘water features’, ‘natural sounds’ and ‘other’ were merged into one category called ‘natural features’. When water features were present, all answers in this merged category were attributed to the factor ‘water features’ and none to the categories of ‘natural sounds’ or ‘other’. To test for the effect of water features, all scenarios were combined and divided into two groups; scenarios 1) with and 2) without the presence of water features. The change in answers given by a participant for comparable scenarios falling into the first and second category were compared. The same procedure was repeated for vegetation, and the effect of vegetation when water was present too.

Table 30 *Results of the separate McNeman-Bowker tests*

Absence vs presence of water features (total)	$\chi^2 = 452.83$	$p < .001$
Absence vs presence of vegetation (when water is present)	$\chi^2 = 4.07$	$p = .539$
Absence vs presence of vegetation (when water is absent)	$\chi^2 = 5.83$	$p = .442$

Table 30 shows the results from the three McNemar-Bowker tests; only the asymmetry between scenarios with- and without water was significant. Vegetation or the vegetation combined with water did not result in significant asymmetries. This means that the choice of the most prominent sound source was significantly different when water features were present, but not when vegetation was visible. An additional Bonferroni post hoc test was carried out to determine what sources caused the asymmetry between scenarios with- and without water features. Four significant effects were found: between aircraft and humans ($p = 0.012$), between aircraft and water features ($p < 0.001$), traffic and water features ($p < 0.001$) and humans and water features ($p < 0.001$). So, the results show that if participants had selected *aircraft, traffic or humans* as the most prominent sound sources in scenarios without water features, they tended to select water features and humans as the most prominent sound sources for the same scenarios containing water features.

Figure 64. Averaged differences from each participant’s mean score for the audibility of the most prominent sound source per scenario. The averaged difference is plotted from the mean per source category and per scenario.

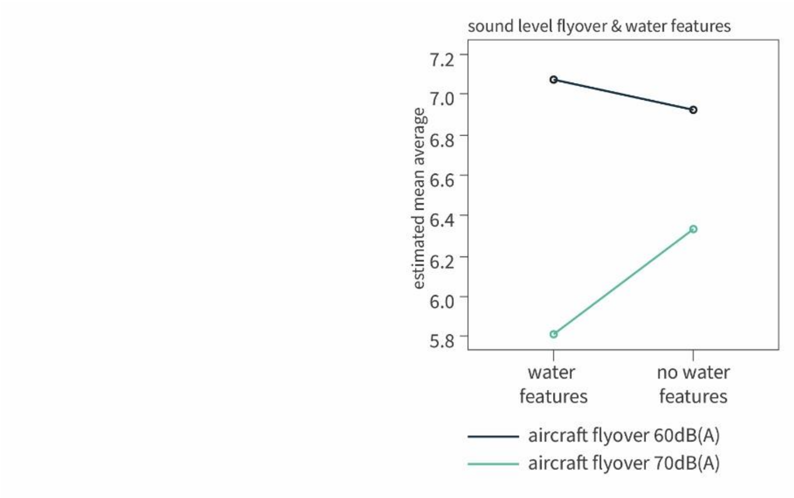

Figure 65. Interaction effect between water features and sound level of the flyover found for the audibility of the most prominent sound source

8.4.2.2. Audibility of prominent sound sources

In the last question, participants were asked to rate the audibility of the most prominent sound source on a 10-point scale between 0 ('did not hear at all') and 10 ('dominated completely'). The data was analysed using a repeated-measures ANOVA based on the average audibility score per scenario. These average scores were independent of the source to which these scores were attributed. The ANOVA revealed main effects for the sound level of the aircraft ($F(1,38) = 4.67, p = 0.04, r = 0.33$), urbanity ($F(1,38) = 13.01, p < 0.001, r = 0.51$) and water features ($F(1,38) = 39.06, p < 0.001, r = 0.71$). Also, the analysis showed an interaction effect between the sound level of the flyover and water features ($F(1,38) = 21.49, p < 0.001, r = 0.60$) (see *Figure 65*). This means that the audibility of the most prominent sound source increased when water was present, but this effect was greater when the sound level of the aircraft was low (60 dB(A)).

A shortcoming of the ANOVA is that it only revealed the within-subject change in audibility scores, without analysing differences between individually selected sound sources. For example, what would happen to the audibility scores of e.g. aircraft if participants selected sound sources other than water in scenarios containing water features, and would the audibility score of such sources increase, decrease or remain unchanged compared to scenarios without fountains? Although the study focused on the effect of water features on the audibility scores of aircraft noise in the first place, all possible sound sources were evaluated.

In a second explorative analysis, the audibility scores per category of the most prominent sound source were studied. Because the absolute ratings on the eleven-point scale may vary between participants, it was decided to focus on the relative within-subject (W-S from now on) change per scenario. This makes it possible to study the relative change between the 32 scenarios clustered for each sound category. For instance, if people selected 'aircraft' or 'traffic' as the most prominent source for comparable scenarios with- and without water features, the expectation was to find similar audibility scores. The average audibility scores for both scenarios would then be similar for this person. The scores for the relative W-S change of the audibility scores per source category where calculated by the following equations.

$$\mu_{person} = \frac{1}{32}\sum_{i=1}^{32} x_i \tag{8.1}$$

$$\mu_{category} = \frac{1}{n_{category}} \sum_{i=1}^{n_{category}} (x_i - \mu_{person}) \tag{8.2}$$

First, the participant’s mean audibility score (μ_{person}) was calculated by including the scores of all the possible 32 answers (x_i). For each of the 32 individual scores, the mean average was subtracted from the individual score ($x_i - \mu_{person}$). This results in the relative difference between the scores attributed to the 32 scenarios. Because the relative scores are linked to the categories of question 6, it is possible to determine the sound source behind the 32 relative scores. In the last step the average scores per source $\mu_{category}$ were calculated based on the combined scores of the participants that selected the same source ($n_{category}$). Figure 64 plots the relative difference in audibility scores per scenario and for the sources participants had indicated, divided in six source categories. The audibility of water features, when selected as the most prominent sound source, was clearly higher than other sound sources. However, even when participants selected other sound sources than water features as the most prominent sound source in scenarios containing water features, in most cases, the audibility scores for these sources were higher than for the same scenarios without water features. This suggests that the presence of water features increased the audibility of the prominent sound source in general, or gave people the impression that the prominent sound source of their choice was more audible. However, as this observation is based on a small sample size, caution is needed in respect to the interpretation of this finding.

8.5. Discussion

This article presented the results of a VR laboratory experiment studying the effects of vegetation and water features on the soundscape perception of areas exposed to aircraft noise. Firstly, the results of the study show that vegetation and water features led to an improvement in the soundscape quality in terms of higher pleasantness and eventfulness ratings. However, as shown in Figure 61 and Table 29, the ratings and effects differ per location and for the sound level of the flyover. For example, the pleasantness ratings for moving water and vegetation are lower for aircraft flyovers with a peak level of 70dB(A). Nonetheless, the effect as measured in percentage change of the soundscape ratings is largest for the loudest flyover in this study. A similar effect was observed for the difference between the two locations. Here, the absolute ratings were lower for the residential area, but the improvement in the soundscape quality as measured by the percentage change of pleasantness and eventfulness ratings was comparable for both sites.

Similar effects of moving water, vegetation and a combination of the two were found in previous studies on soundscape quality and (road) traffic sources [see e.g. ,16,30]. However, in comparison to earlier studies, the effect size of the interventions (vegetation, water, combined) is smaller or similar, which can be attributed to various factors. For example, studies vary in the choice of research methodologies, metrics, selection of location(s), (average) sound levels and cultural backgrounds. The variations complicate to comparison of the results of this article with earlier work. Moreover, vegetation in urban settings does not indicate that more trees automatically improve the soundscape quality. Instead, visual and auditory expectations have to be in harmony, which means that trees in an urban setting are different than trees in a forest [31,35]. Additionally, the results do not disclose to what extent the source should be visible or screened. Literature suggests that a higher level of visual screening led to a higher noisiness rating [33]. Aircraft noise might have an even stronger effect, as general attitude towards aircraft is, among other factors, related to safety concerns associated with e.g. the probability of a crash [20,59]. Visibility and being able to see the aircraft may evoke a sense of control, thereby possibly improving the soundscape perception. However, more research will be needed to study this effect. The same applies for water features, as the study combined the visual design of the fountain and sound level of the water jets. The question remains as to what would happen if the sound level was louder or quieter. Also, was it the auditory sensation that rendered the positive response or did the visual qualities of the fountain also play a role? Similar questions remained after a previous in-situ study where the water sound of a fountain, in itself, had no effect on the soundscape perception of a park [29]. In other words, although the overall soundscape quality improved when the fountain was switched on, the water sound had no significant effect on the soundscape quality. Instead, it was suggested that the water sound improved the soundscape indirectly, because it reduced the audibility of traffic. The researchers attributed this effect to auditory masking effects diminishing the attention and audibility of the traffic sounds.

A third observation was that the presence of water features influenced the ranking of sound sources in terms of auditory dominancy. Aircraft and general traffic sounds seem to have been reduced in saliency and dominancy, pointing to a change in the constellation of fore- and background sounds. The presence of moving water did not only change which sources were indicated as most prominent, but also increased the perceived audibility of these sources. The results showed a significant increase in the audibility scores in the presences of water features. Results from an additional explorative analysis showed that the audibility of almost any source, if indicated as the most prominent source, increased when water features were present. This was a somewhat surprising outcome and suggests that moving water seems to act as an acoustic filter or masker, limiting the sources' audible. In other words, participants who selected sounds other than moving water, although it was present, seemed to hear these sounds more clearly because the water sound subdues the signals of quieter sounds. In fact, this reduces the range of sounds to choose from. Based on literature, this might be linked to non-energetic or informational masking [26,27]. In this context, masking is seen the auditory similarity between target and masking stimuli, creating uncertainty about the origin and masker sound(s) and a competitive selection process [27,60]. The acoustic signal is confused with the sound maskers, i.e. moving water, which can suppress audibility and distort and change focus and saliency [26,61]. The results suggest that, for most scenarios, water features overshadowed aircraft and traffic sounds in saliency. From a theoretical perspective, adding a masking sound can mean that the threshold to hear other sound sources increases, which mean that quieter sounds are not clearly distinguishable any longer [26]. The results suggest a similar response during this experiment, e.g. the formation of a hearing threshold emphasizing specific sounds, attentional distortion and competition. However, as the sample size was small, more research on these individual aspects is needed, e.g. acoustic ‘amalgamation’ of frequency spectrums and informational masking in relation to complex visual environments.

8.6. Conclusions

Based on the results and discussion, the following conclusions can be drawn about the individual and combined effects of moving water and vegetation on the soundscape quality of residential and commercial areas exposed to aircraft noise varying in loudness. Both moving water and vegetation led to a significant improvement of the soundscape quality defined as the pleasantness and eventfulness of the soundscape:

- Compared to the baseline scenarios without vegetation and water features, the relative improvement of the soundscape quality that can be attributed to moving water and vegetation are largest for flyovers with a L_{Amax} of 70 dB(A) compared to 60 dB(A). On average, soundscape ratings, i.e. the averaged scores of soundscape pleasantness and eventfulness combined, were respectively 6% (60 dB(A)) and 10% (70 dB(A)) higher when either moving water or vegetation was present.
- On average, the eventfulness of the soundscapes increased by 20% (60 dB(A)) and 26% (70 dB(A)) respectively, for scenarios with both vegetation and moving water. Average pleasantness scores increased by 13% (60 dB(A)) and 16% (70 dB(A)) respectively.
- When present, moving water was more salient than other sound sources. Also, moving water had a significant effect on the order of what was denoted as the most dominant sound source. For instance, on average, moving water was perceived as a more dominant sound source than aircraft and other traffic sound sources, changing the order of fore- and background sounds.
- The presence of moving water led to an increase in the audibility score of the most prominent sound source per scenario. Further analyses of the data suggest that the audibility scores for

all sound sources increase, regardless of the category. This may be attributed to aspects of informational masking and an acoustic filter, or hearing threshold evoked by the sound of water.

- A MANOVA analysis showed that the metrics used to measure the overall quality, visual quality, auditory quality and auditory pleasantness are not orthogonal and thereby independent. This is especially important when virtual reality is used to carry out soundscape research.

The results of the study show that soundscape interventions like moving water and vegetation can contribute to a better perceptual quality of areas exposed to aircraft noise. Implementing such interventions can complement noise abatement strategies used by urban design practitioners. The results also open new avenues for future research, especially on the in-situ application of water and vegetation, and also on auditory masking effects.

8.7. Literature

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conclusion

9. Conclusions, reflections and recommendations

The results of the four research chapters cumulate here, in the final conclusions. First, the chapter will answer the research questions, by giving concise answers followed by a more elaborate reflection on the results. After the final conclusion, the chapter expands its horizon to the future, with a series of recommendations for practice and future research.

9.1. Final conclusions and discussion

The central question was broken down into four sub questions, each covering one aspect and study. Before the main question is answered, the results for each study are discussed individually, and followed by the final conclusions and reflections.

> *Question 1: To what extent do buildings reduce aircraft noise in areas that are not directly underneath flight paths as the distance between the aircraft and a receiver increases?*

Answer

Buildings can reduce aircraft noise substantially, with L_{Amax} and L_{Aeq} levels above 10dB(A) lower near shielded facades compared to facades facing towards the flight paths. The sound reducing effect is stronger for locations closer to the ground track of an aircraft flyover and for lower flight altitudes.

Discussion

The results from the first study show that buildings located at a substantial horizontal distance from a flight path can reduce the level of aircraft noise locally. The results from the measurement study showed a clear difference between the noise levels at facades facing towards or away from the flight path, i.e. exposed and shielded facades respectively. This results also suggests that the horizontal distance between the ground track of a flight path and a building does influence the level of noise reduction buildings can facilitate. However, this finding can be interpreted in two different ways. Firstly, due to ambient noise, the relative difference between exposed and shielded facades will always be smaller for buildings at a greater horizontal distance from a flight path. This means that the noise reduction can only be measured if the aircraft noise exceeds the ambient noise level near both sides of a building. Secondly, as sound waves are scattered on their path through the atmosphere, the sound field becomes more diffuse with the propagation distance. Around buildings located at a greater horizontal or vertical distance from a flight path, the sound waves will be more scattered and hit the buildings at different angles. Consequently, the noise shielding provided by buildings will be lower for location C compared to location A and B (see figure 1, chapter 5 for the locations). This would also explain why the predictive value of the slant angle is better for location A and B than C for the variance in the sound reduction around buildings. Despite the fact that the slant angle shows a significant correlation with the noise reduction around buildings, most of the variance is not explained by the source's position alone. This means that other factors, such as wind and temperature effects, as well as building geometry, have a strong influence on the reduction of aircraft noise around buildings. The sound-abating potential of buildings and locations also depends on the flight direction. If an aircraft makes a turn around a building, the exposed and shielded facades will reverse.

Question 2: To what extent can urban acoustic models predict aircraft noise around buildings with an acceptable accuracy without considering atmospheric effects?

Answer

To predict the noise reduction around buildings in an urban acoustic model, atmospheric effects can be omitted if the slant angle between a building and the position of an aircraft is greater than 15 degrees. However, if the slant angle is lower, the ray-tracing model overestimates the noise reducing effect of a building. The numerical results are significantly closer to measurements if a curvature is added to the rays, based on a moderate linear speed of sound gradient, simulating a refracting atmosphere.

Discussion

The results from the second study show that (ray-tracing) urban acoustic models can be used to predict the propagation of aircraft noise around buildings. As in the reference study, the results show that for slant angles >15 degrees, calculations with and without a refracting atmosphere are similar. The results also show that the simulation approach, i.e. approximating an aircraft flyover as a sequence of point sources, as used in numerical models used to auralize aircraft noise, can be applied for the urban acoustic model. Thus, it can be concluded that this simulation method also yields accurate results in ray-tracing urban acoustic models. However, if the slant angle between an aircraft and a receiver is <15 degrees, or when the aircraft's altitude is substantial, refraction becomes increasingly relevant. A comparison between numerical predictions and the (aggregated) measurements showed that the numerical model used in this study overestimates the noise reduction around buildings if a non-refracting atmosphere is assumed. Similarly, the results for the linear approximation of a logarithmic atmospheric profile (as used in the Harmonoise and Nord2000 methods) were not significantly different to those from a non-refracting atmosphere for most locations and frequencies. For a typical summer day, the results for a vertical linear speed of sound gradient of $0.006s^{-1}$ were better attuned with the measurements than the other values in this study. Despite the overall comparison between the measurements and numerical results, differences up to 6dB were found for incidental frequencies, around individual buildings for the predicted maximum noise reduction around a building. The model is believed to be acceptable for the purpose of a comparison study, and to estimate the ΔL_{max} during a flyover, in which a ray curvature mitigates the risk that the noise reduction is overestimated. However, in terms of the ΔL_{eq} based on a full flyover, the differences between the measurements and the simulation methods are on the borderline of the accepted definition of model errors. The results show that the numerical results for the best gradient are slightly conservative in comparison to the measurements. As the weather variations in this study were relatively small, and represent typical weather during summer in Northwest Europe, it was not possible to evaluate whether different speed of sound gradients correlate with specific weather types.

> *Question 3: To what extent can the design of buildings and street canyons improve the reduction of aircraft noise locally within areas that are not directly underneath flight paths?*

Answer

For locations with a substantial horizontal distance of the ground track of a flight path, the building geometry (loggias and overhanging roofs), building height, the width between facades and the surface cladding have a significant influence on the reduction of aircraft noise around buildings. Compared to a baseline scenario, for specific frequencies, the added noise reduction can be well above 10dB.

Discussion

The results of the third study show that carefully designed building geometry and surface materials result in a significant abatement of aircraft noise. Compared to a baseline scenario, i.e. a typical terrace house with two stories and a saddleback roof, the sound levels near shielded facades are significantly lower after the building height was increased and the facades were clad with vegetation. Alternatively, buildings with overhanging roofs, loggias and green walls yielded a comparable sound-abating effect near the shielded facades. However, the study showed that as a stand-alone measure, green walls did not induce a significant noise attenuating effect. Tilting the facades also barely affected the sound level near the shielded facades, although the sound level near exposed facades dropped locally. The orientation of streets, i.e. parallel or orthogonal to the direction of the flight path, blurs the difference between shielded and exposed facades. Although the equivalent sound pressure level can still vary within a canyon, the maximum exposure level will be similar near both facades. Thus, from an aircraft noise attenuation perspective, it is best for buildings and streets to be placed in parallel to the direction of a flight path. Thus, in addition to the noise reduction around buildings in the baseline scenarios, the design variables of ‘height’ and ‘overhanging roofs and loggias’ combined with ‘green walls’ further reduced the sound level near the shielded facades significantly. However, the exact level of sound reduction depends on the location, canyon profile and the frequency of the sound. For locations relatively close the flight path, the results show that a narrow canyon can reduce, or in the worst case negate, noise-abating effects due to trapped reflections between the buildings. While reflected sound waves can leave the canyon if the building heights are relatively low, second or third order reflections will amplify the sound levels in a canyon that has tall buildings on both sides.

This issue can be partly resolved by applying absorbing materials inside the canyon, but this will be less effective for lower frequencies. The extra noise reduction of the peak exposure level, compared to the baseline scenario, is estimated to vary between 5dB (63Hz) and >20dB (500Hz) for a building height increase of 12m with green walls, and between 5dB (63Hz) and 15dB (500Hz) for the addition of overhanging roofs, loggias and green walls.

> *Question 4: To what extent can visual and auditory natural features improve the soundscape quality of urban areas exposed to aircraft noise?*

Answer

The presence of natural features, either visually, auditory or a combination of both, improve the soundscape quality of urban areas exposed to aircraft noise. The effects are in line with the results of previous studies which focused on the positive effects of natural features in relation to road traffic noise.

Discussion

The fourth study focused on the impact moving water and visible vegetation had on the soundscape quality. In the first instance, the soundscape quality refers to the perception of the acoustic environment, which is influenced by both acoustic and non-acoustic factors. The results of the study showed that both interventions, i.e. moving water and vegetation, improved the soundscape quality of urban areas exposed to aircraft noise. To improve the soundscape pleasantness, the impact of visible vegetation was greater than moving water. However, moving water clearly reduced the saliency of air and road traffic noise. This changes the constellation of fore- and background sounds and the audibility of the most dominant sound source. The presence of moving water seems to act as an auditory masker, confusing the auditory signal of the unwanted sounds and masking them. The soundscape pleasantness scores for scenarios exposed to an aircraft flyover with an L_{Amax} of 70dB(A), but with either visible vegetation or moving water, were comparable to the scores for the baseline scenarios exposed to aircraft noise with an L_{Amax} of 60dB(A) without either of the two interventions. This suggests that the effect induced by the interventions is comparable to a reduction of the L_{Amax} by 10dB(A) for the soundscape pleasantness. The combination of both interventions had a clear cumulative effect, but it is difficult to quantify the equivalent reduction other than it being >10dB(A). The presence of visible vegetation or moving water also increased the eventfulness of the soundscape. Although the study shows that moving water and the visibility of vegetation increase the soundscape pleasantness, the character of soundscapes will still be invigorating and typically urban. More research is needed to study whether the addition of natural features could change the perception of soundscapes polluted by aircraft noise to tranquil or restorative.

The answer to the overarching research question builds on these four previous conclusions. The central question of this thesis was:

> *How can urban and architectural design reduce aircraft noise exposure and improve the soundscape quality for areas exposed to aircraft noise?*

Based on the four studies, it can be concluded that applying a combination of urban and architectural design strategies can improve the soundscape quality of areas exposed to aircraft and/or lead to a reduction of the sound exposure level. However, the impact and suitability of design strategies depend on the receiver's location in relation to the flight path. In areas underneath flight paths, the urban and architectural design will barely reduce the sound pressure levels at all. Nonetheless, natural features, such as moving water and visible vegetation, can still improve the perceived quality of the soundscape. The results suggest that these interventions might yield an effect comparable to a reduction of 10dB(A). As these interventions also make the soundscape more eventful, the auditory ambiance of the areas will typically be more urban and invigorating, but not necessarily restorative or tranquil. The study shows that especially areas exposed to high levels of aircraft noise might benefit from natural features.

For areas that are not directly underneath a flight path, the shape and cladding of buildings can reduce the sound pressure levels near shielded facades. Increasing the building height or adding overhanging roofs and loggias to the buildings, in combination with green walls, can reduce the sound levels significantly. In some cases, this could reduce the distinctive tonal components of aircraft noise to well below the ambient noise level. However, the noise reducing potential of buildings also depends on the space between buildings. While narrow canyons can increase the noise abatement for buildings at a substantial horizontal distance from a flight path, the opposite is true for locations closer to the aircraft. Mounting porous materials on the walls inside the canyon can lessen this problem, although the beneficial effects will be small for low-frequency noise.

As with areas underneath a flight path, natural features can also improve the soundscape quality of areas at a greater horizontal distance from a flight path. Additionally, if natural features are positioned near shielded facades, the character of the soundscape can be changed or enhanced. This means that the buildings can reduce the aircraft noise levels, while moving water and visible vegetation give off a masking effect. This might further decrease the saliency of aircraft noise and evoke a more tranquil or restorative auditory experience compared to at locations without buildings. To conclude, the findings stipulate that it is the very combination of acoustic and visual interventions that have the power to change acoustic environments exposed to aircraft noise for the better.

9.2. Recommendations for further research

The research raised various new questions for future research. The topics are grouped into three categories and discussed accordingly.

9.2.1. Measurements and implementation

Firstly, gathering long-term data could provide a wealth of information about the sound levels around buildings for a wider variety of weather types and seasons. Secondly, this data also could be used to examine the role of meteorological conditions as a predictive factor for the level of noise abatement more extensively. Thirdly, collecting data over the full perimeter of a building and charting the sound field in between buildings is recommended. This would provide a better picture of to what extent the sound level changes with the height of a building, or the level/rate of sound decay behind a building. Fourthly, although the study found no significant results for green walls as an isolated measure, additional (in-situ) research is recommended to verify this conclusion, because both the calculation method and the material specifications were relatively conservative. Hence, the sound reduction yielded by green walls might be higher than predicted by the numerical model. Fifthly, with sound reductions >10dB(A) near some of the buildings, it would be advantageous to study whether quiet building sides can also lower annoyance rates for aircraft noise. Sixthly, further research is needed to identify the possible influence of the building geometry on the interference of (low frequency) sound waves in bays or in between buildings. Finally, to improve the numerical model, it would be beneficial to test the findings with full scale models. For example, stacked shipping containers could simulate a building or streets whilst allowing flexibility to rearrange the configuration.

9.2.2. Numerical methods

Firstly, long-term data could help to study the relation between (linear) speed of sound gradients and meteorological factors. Based on such information, it could be determined which gradients correspond with specific weather types. Subsequently, this would also broaden the opportunities to study the sound exposure around buildings under various weather conditions. Secondly, it is also recommended to validate the model with results from wind tunnel tests. This gives more freedom to control the dependent and independent variables, and to study which factors are critical. Finally, the ray-tracing heuristic method as used in this research has a lower fidelity than wave-based numerical methods. However, thanks to ongoing research on wave-based acoustic models and CFD and in computers becoming increasingly fast, wave-based numerical methods will become more attractive and viable ways to predict aircraft noise around buildings. This could lead to research on the application of such models to cases comparable to those discussed in this thesis. For example, numerical predictions from the open-source PSTD could be compared to the measurements presented in this study.

9.2.3. Natural features and soundscapes

Firstly, to study the short- and long-term effects of natural features, it would be best to repeat the VR study in-situ. Secondly, the study only focused on public areas (squares and streets), but not on gardens. Hence, repeating the study for more private outdoor environments, such as gardens, preferably with participants living in the dwellings concerned, could provide more insights. Thirdly, future research could compare the foliage density and coverage, or the perception of aircraft noise in combination with different fountain designs. Fourthly, the impact source visibility has on the perception of aircraft noise, in relation to the effectiveness of natural features, should be studied. Often people's attitudes towards aircraft, and by extension aircraft noise, are coloured by the associations they make between aircraft and their own fear of flying or plane crashes. If the aircraft noise source is screened off by trees and out of view, this might either improve or worsen the perceived soundscape quality. Finally, it would be advisable to study the response to aircraft noise, in combination with natural features, for more than two sound levels. This would make it possible to improve the estimations for the equivalent noise reduction of moving water and/or visible vegetation.

9.3. Recommendations for design practice

These results can be applied in real world projects, but the level of noise reduction, or soundscape improvement, will depend on the local noise situation. This requires a rigorous analysis of the mean flight paths and sound pressure levels around a location before further advice can be given. Once the acoustic analysis is finished, the appropriateness of individual or combined measures can be predicted. Consequently, airports and cities could use the results for spatial noise abatement action plans. Such plans could specify to what extent the architectural and urban planning could improve the acoustic environment, based on the flight routes and sound pressure levels around the flight paths. Ideally, this could help architects, designers and developers to include aircraft noise as a design parameter in their proposals. Aside from adding more trees or moving water, the implementations will be easier to realise in locations without a pre-existing urban fabric. However, this doesn't mean that the research cannot play a role in urban retrofitting. Although the challenge will be greater, and the level of complexity higher, the numerical model described in this thesis can help design teams to examine the acoustic impact of proposals and design variants.

10. Acknowledgements

Without saying, I owe an awful lot of gratitude towards everyone who has supported me throughout the doctoral research over the past three years, either in Cambridge, London, the Netherlands or elsewhere. In the first place I want to thank my supervisor, Professor Koen Steemers, and my academic advisor, Professor Jian Kang, for their time, wisdom and feedback, and their words of encouragement and motivation. Secondly, I want to thank Maarten Hornikx, Dick Bergmans, Paul Eijssen, Kim White, Merve Karacaoglu, Merlijn den Boer and Sander Heblij, and my colleagues at NLR for all the witty and inspiring conversations we had during the coffee breaks in Amsterdam, but also for their critical and extensive support. Thirdly, I want to thank Marc Frowijn, Ine Kuipers, Jurjen Tjarks, Joost van Faassen, Gerard Willemsen, Evert Bron and Arjen van Nieuwenhuizen for their time, energy, feedback and ideas, always with the practical application of the research in mind. Fourthly, I want to express my gratitude to Bert Uitterhoeve for his support, encouragement and endeavours for helping me to forge alliances essential to secure the funding of the research. Fifthly, I want to thank my family and friends in Britain and the Netherlands for all good company, love and distraction, keeping me with both feet on the ground. A special word of thanks goes to ‘Rotterbamb’ (Kees, Bas and Steven), in the first place for their generosity to offer me a permanent room, ‘the cupboard’, but more importantly, a reasonably priced ‘pied-a-terre’ in the Netherlands. Finally, I want to thank Anna for listening to the never-ending stream of (daily) PhD-related monologues and helping to translate the manuscript from Dunglish to English.

A. Appendix A: Collaboration and funding

A.1. Collaboration and funding

The research was made possible through financial support from the Cambridge Trust, Netherlands Aerospace Centre (NLR), city of Amsterdam, Province of Noord-Holland and the municipality of Haarlemmermeer. The partnership with NLR made it possible to use in-house equipment and (technical) expertise which was essential to carry out the research. At the start of the research, it was agreed that the intellectual property of the work was shared between the author and NLR. Additional subsidies were awarded by the province and municipalities involved in the project, while the funding bodies waived the right to influence the project academically. Although rare at the Martin Centre for Architectural and Urban Studies at Cambridge University, this form of public-private funding is more common in science and engineering research. The funds were utilised to hire technical (student) assistants for the data collection for the study in chapter 5, and for the study in chapter 8. More details about their involvement in both studies can be found in appendix A.

Aside by the input from people within the department and university, academic support was sought from fellow academics at Eindhoven University of Technology (Dr Maarten Hornikx), the University of Ghent (Professor Dr Dick Botteldooren and Professor Dr Bert de Coensel) and Stockholm University (Professor Dr Mats Nilsson).

A.2. Collaboration per chapter (other than the supervisor and advisor)

A.2.1. Chapter 5

For the first research chapter (chapter 5), the author reached out to Dr Maarten Hornikx (Eindhoven University of Technology) (MH from now on) for feedback and input on the initial research proposal. The actual experiment was carried out with the help of five student-assistants, hired for a tenure of four weeks (summer 2016). Four students helped to collect the data and one student was instructed how to screen the data. This student worked on the manual detection of aircraft flyovers in the data-set and the contamination of the data by sounds from sources other than aircraft. MH also gave feedback on the written content of the chapter, recently submitted as a separate journal article.

A.2.2. Chapter 6

As for the fifth chapter, MH was consulted for feedback and input on the initial research proposal (for research chapter 2). Based on his suggestions it was decided to compare the application and appropriateness of the acoustic simulation models CadNa, PSTD and OTL. The author decided to select OTL as the preferred acoustic simulation package for this study.

A.2.3. Chapter 8

For chapter 8, the research was supported by a research assistant (Merve Karacaoglu, MK from now on), who is trained as a research psychologist. MK was hired for a tenure of six months by the author and NLR after an initial research plan had been drawn up by the author of this thesis. On top of that, Kim White (KW from now on), a fellow PhD researcher at NLR, helped to author and MK in an advisory position. Like MK, KW is a research psychologist, and was working as a PhD researcher at the department of Applied Psychology at the Vrije Universiteit Amsterdam and NLR by that time. The main reason to seek for additional support from MK and KW was the author's limited experience with psychological experiments. This was also explicitly advised by the reviewers during the first year's viva in 2016. During the first month of the tenure (November 2016), MK was asked to review the initial research proposal, based on her experience and background, and to propose changes where needed. Also, the author collaborated with MK and KW to develop and translate the questions for the questionnaire from English to Dutch. Although the author had proposed a repeated-measures ANOVA to analyse the data in the initial proposal, the author and MK worked closely together to improve and detail the data collection procedure. The author was responsible for the selection of the two sites, and 360 videos (and audio) were shot together with MK. MK stitched and combined the footages from the individual camera, with the help of NLR's IT / VR team. NLR's multimedia department also removed any remaining or existing traces of greenery from the videos. The author calibrated and edited the binaural audio files. The animations and videos were created by NLR's VR team (Henk Lania / Roalt Aalmoes) in Amsterdam, supported and supervised by the author and MK. In the meantime, the author contacted the ethics board of the Psychology department at the University of Cambridge to get formal ethical approval for the experiment. As the experiment would take place in Amsterdam, the ethics board needed detailed information about the research and insurance policies involved. The final confirmation of the board's approval was given in January 2017. The author also reached out to Prof Dr Mats Nilsson (Stockholm University) for excerpts from water features collected during a previous study. Also, the author contacted Prof Dr Dick Botteldooren and Prof Dr Bert de Coensel (University of Ghent) for feedback on the questionnaire, and feedback and advice for the translation of questions from English to Dutch.

Before the actual experiment, the author and MK ran a pilot study with five people at NLR to verify and amend the research procedure. Based on the outcomes of the first trials, the research protocol was changed and improved. The experiment was carried out at Vrije Universiteit, were we could use a laboratory with access to a pool of student participants, by the courtesy of KW. The author and MK carried out and discussed the first few experiments together, after which MK continued the data collection alone, while the author supervised the project from Cambridge. Before and during the experiment, MK made a template for the data in SPSS and inserted/processed the data after each participant. This also allowed MK and the author to run statistical tests after each participant and to follow the results of the experiment meticulously. Before MK's contract terminated in April 2017, MK kindly structured the relevant literature and data in folders, and wrote a description of the protocols and scripts the team had followed during the experiment.

After the experiment, KW raised questions about the extent that certain factors (questions) were (in) dependent, based on the results of a quick factor analysis. Hence, the author built and carried out an additional repeated-measures MANOVA, and decided to restructure the data and, where needed, additional analyses. Although the repeated-measures ANOVA tests were generated and discussed during the experiment, all other statistical tests and analyses were carried out after the experiment, by the author alone. All the written content is of the author's hand, although MK and KW kindly gave feedback on the text during the writing process.

B. Appendix B: Publications

B.1 Scientific journals

- Lugten, M., Karacaoglu, M., White, K., Kang, J. & Steemers, K. *Improving the soundscape quality of urban areas exposed to aircraft noise by adding moving water and vegetation*. Journal of the Acoustical Society of America 144, 2906-2917 (2018).
- Lugten, M., Hornikx, M., Kang, J. & Steemers, K. *The quiet side of buildings exposed to aircraft noise: in situ-measurements on the noise reducing capacity of buildings during take-offs*. Building and Environment (under review).

B.2 Conference papers

- Lugten, M. & Kang, J. *An experimental study on the shielding performance of buildings exposed to aircraft noise comparing measurements near front and rear facades*. INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Hamburg (DE), 2679-2689 (2016)
- Lugten, M., Karacaoglu & M., White. *A VR experiment testing the effects of fountain sound and visible vegetation in areas exposed to aircraft noise*, INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Hongkong (CN), 3682-3690 (2017)

B.3 Book chapters

- Lugten, M. Schiphol verankert, een stedenbouwkundig archetype voor de luchthavenregio, in De adaptieve luchthaven, Schiphol naar de toekomst, red. de Jong, B. & van Faassen, J. nai010 publishers (2016)